NAS 1.21: 6101(05)

NASA SP-6101 (05)

OCT 21 1992

ISSUES IN NASA PROGRAM AND PROJECT MANAGEMENT

COMPLETED

Q.M.

NASA

NASA SP-6101 (05)

ISSUES IN NASA PROGRAM AND PROJECT MANAGEMENT

edited by

Francis T. Hoban

Program Manager

NASA Program and Project Management Initiative

National Aeronautics and Space Administration
Office of Management Systems and Facilities
Scientific and Technical Information Program
Washington, DC 1992

Issues in NASA Program and Project Management

A Collection of Papers on Aerospace Management Issues

National Aeronautics and Space Administration **Spring 1992**

1 **An Overview of the Project Cycle** **Dr. Kevin Forsberg and Hal Mooz**
The founders and co-principals of the Center for Systems Management in California stress the importance of "front-end" activities in the project cycle. Their analysis of concept selection, design, development and operations is a proposed standard for the aerospace industry.

7 **SE&I Management for Manned Space Flight Programs** **Owen Morris**
The co-founder and new CEO of Eagle Aerospace in Houston explains how systems engineering and integration has worked over the past 30 years on increasingly complex programs. He was with NACA and then NASA for 32 years, serving as Manager of the Lunar Module Project, the Apollo Spacecraft Program and Space Shuttle Systems and Engineering.

24 **Shared Experiences from NASA Programs and Project: 1975** **Frank Hoban**
Part two covers six more NASA projects studied at a two-day workshop hosted by the National Academy of Science. The editor, now a visiting fellow in management at the George Mason University, concludes with a summary of lessons learned and recommendations made that year to the Deputy Administrator.

32 **Cost Control for Mariner Venus/Mercury '73** **John R. Biggs, Walter J. Downhower**
The Office of Space Science and the Jet Propulsion Laboratory Project Engineering Division, respectively, did a thorough analysis of cost control on the first OSS-managed project designed and developed within original schedule, performance and cost estimates.

42 **The Shuttle: A Balancing of Design and Politics** **Dale D. Myers**
NASA's former Deputy Administrator shares an inside story on the planning and development of the Space Shuttle from 1969 to 1971, from the White House to NASA Headquarters. Dale Myers served as NASA's Associate Administrator for Manned Space Flight from 1970 to 1974 and wrote this piece at request of the NASA Alumni League. Attached is a 1972 report on the evolution of the Space Shuttle configuration by Charles J. Donlan.

49 **Resources for NASA Managers** **William M. Lawbaugh**
New holdings for the NASA Program and Project Management Institute (PPMI), plus an assortment of new books of value and interest to managers and aerospace professionals.

SP-6101(05) Issues in NASA Program and Project Management is fifth in a series from NASA's Program and Project Management Initiative. This series is collected and edited by Francis T. Hoban with Dr. William M. Lawbaugh. Statements and opinions are those of the authors and do not represent official policy of NASA or the U.S. Government. Useful and enlightening material is welcome, and diversity of ideas is encouraged.

Inquiries should be directed to Francis T. Hoban, Program Manager, Office of Human Resources and Education, Code FT, NASA Headquarters, Washington, D.C. 20546-0001.

An Overview of the Project Cycle

by Kevin Forsberg and Hal Mooz

Projects are formed to achieve defined objectives, which almost always include a set of technical requirements to be achieved within budget and schedule constraints. The Project Cycle is a tool that defines the typical project activities and their logical progression from the beginning to end. Many projects encounter serious difficulty and often fail because the project team ignores the proper sequencing of activities and events in the project cycle, particularly the "front-end" activities. Studies, such as the Hearth Committee report (NASA) and the Packard Presidential Commission report (DoD), emphasize the importance of not ignoring, bypassing, or improperly sequencing essential project cycle events. To comply, project managers must completely understand their project's cycle.

Many functional managers attempt to define the project cycle from their perspective. These attempts result in the Budget Cycle, the System Development Cycle, the Acquisition Cycle and many other focused views of the typical life of a project. Development of a comprehensive project cycle has been hampered by the inability of the many interest groups involved to achieve consensus. Moreover, engineers tend to be reluctant to create a typical project cycle in fear that it will reduce their freedom to be innovative during the engineering portion of the cycle.

Under contract to the U.S. Government, we have studied and evolved a baseline project cycle useful for all projects requiring concept selection, design, development, and operations. While fundamentally similar to the NASA planning process that includes Phases A, B, and C/D, it provides markedly clearer terminology, and has been carried to a depth of detail not previously available.

Project Cycle Definition

The project cycle is an illustration of the typical and necessary project events sequenced from beginning to end. There are three aspects or layers to the project cycle, each containing its own set of events. These layers are the Budget, Business, and Technical aspects.

The Budget aspect contains all events relative to securing the necessary funding required by the project. The Business aspect contains all the events relative to the overall programmatic management of the project, including the acquisition process and associated contract management. The Technical aspect contains all the technical events relative to determining and satisfying the technical requirements of the project, and validating that the project solution complies with the requirements.

The interwoven events for these three aspects constitute the total cycle. Each event or product of an event is assigned to one of four interrelated categories: Budget, Activities, Products, and Control Gates. See Figure 1, Project Cycle (Partial View), which shows these four categories of events and related products.

The "budget events" define the required planning for and securing of project funding and are keyed to important U.S. Government fiscal milestones imposed by the Office of Management and Budget (OMB).

The "activities" include all sorts of actions such as to study, analyze, evaluate, select, design, etc.

The "products" consist of activity results such as specifications. drawings and manuals; internal hardware and software such as technical feasibility models; and the deliverable hardware, software and documentation.

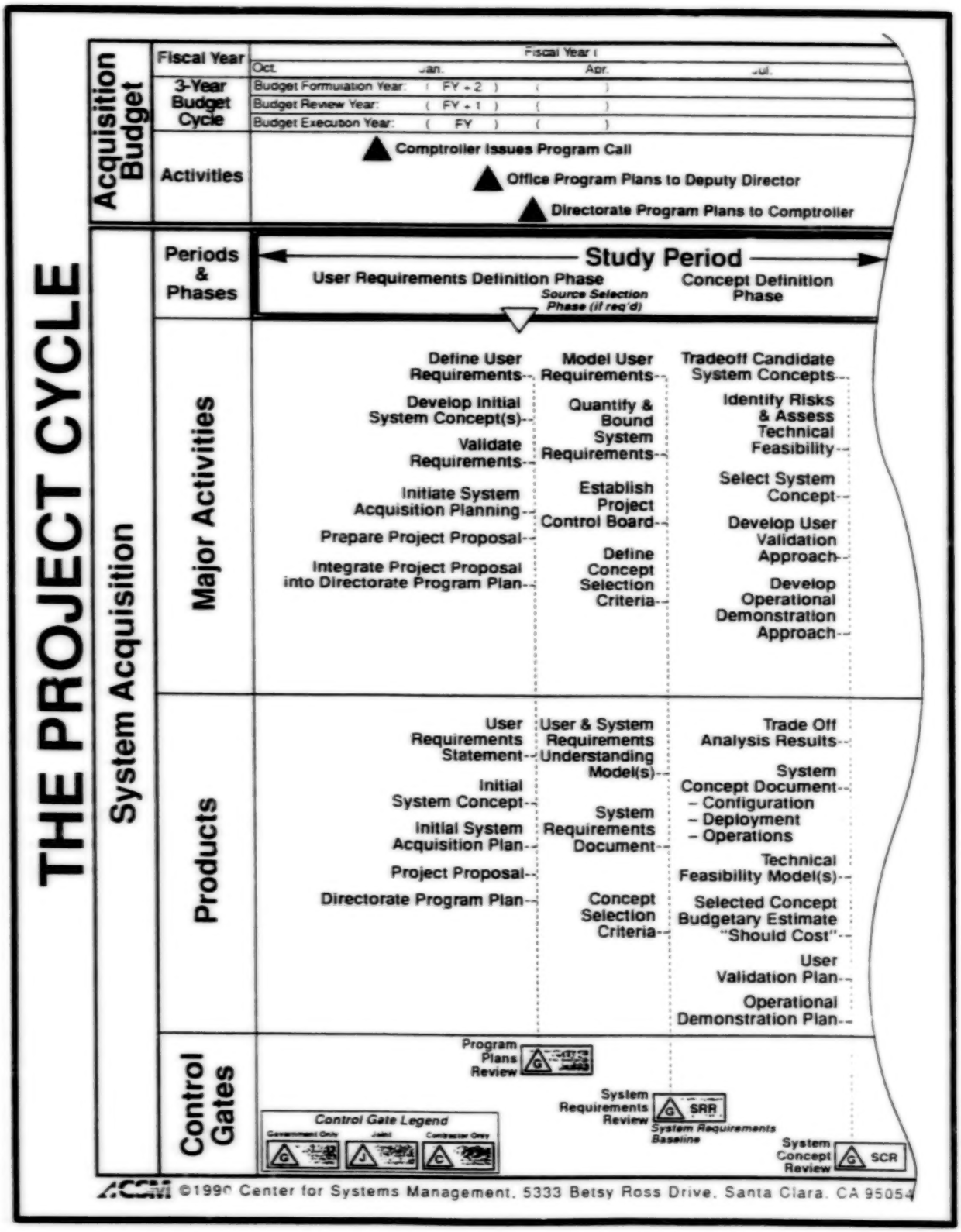


Figure 1 - Project Cycle (Partial View)

The "control gates" are predetermined, formal status and decision checkpoints which must be satisfied, or else the project is not sufficiently prepared to move on to future events without increased risk.

Project Cycle Periods and Phases

The project cycle is usually divided into periods and then further subdivided into phases. Our typical cycle is divided into the Study Period, the Acquisition Period, and the Operations Period. These periods depict the three major periods of a project that progresses from an identified user need, through concept determination, contractor participation for development, and ultimately to user operation.

The "Study Period" consists of four phases. They are the User Requirements Definition Phase (commonly known in NASA as pre-Phase A), the Concept Definition Phase (commonly known as Phase A), the System Performance Definition Phase (commonly known as Phase B), and the Acquisition Planning Phase.

The "Acquisition Period" consists of the Source Selection Phase and the System Development Phase (commonly known as Phases C/D).

The "Operations Period" consists of the Deployment Phase and the Operations and Maintenance Phase. It is sometimes called Phase E.

The objective of the "User Requirements Definition Phase" at the start of the Study Period is to determine exactly which of the user's total requirements will be included and satisfied by the proposed project. Usually, user requirements are more comprehensive than can be reasonably or economically incorporated into a single project. Considerable analysis, negotiation and decision making must occur to identify the project's subset of the user's requirements, which are then recorded in the project's System Requirements Document and signed off by both the user and the project manager. In addition,executive approvals for the project and initial project funding are secured. The need to control requirements, of course, is understood.

The prime objective of the "Concept Definition Phase" is to select the preferred concept from possible candidates, and then to develop the budgetary "should cost" estimate and the "should take" schedule, and then to identify and resolve any areas of high risk. The System Performance Specification and the Interface Specifications are developed during the System Performance Definition Phase so that the selected system can be competed for the marketplace. During the Acquisition Planning Phase the approach to the acquisition is developed and documented in the Acquisition Plan, and a credible, qualified bidder's list is prepared. If the project can be performed totally internal to NASA, the justification for this approach will be determined in this phase.

The objective of the "Source Selection Phase" is to select through fair and open competition the best value through the comprehensive, analytical evaluation of contractor proposals. The system concept is designed, produced, verified and delivered during the "System Development Phase." The events of this phase ensure that the concept is in full com-pliance with all contractual requirements.

The main objective of the "Deployment Phase" is to transfer the system from the contractor's facility to the operational location, and then to establish full operational capability of the system. The system is operated and evaluated in terms of the success of the system in meeting the original project objectives during the "Operations and Maintenance Phase."

The Technical Aspect of the Project Cycle

The Technical Aspect of the Project Cycle can be viewed as a "V" formation within the project cycle (see Figure 2, Overview of Technical Aspect of the Project Cycle). While budget and business events can typically be compressed and accelerated, the technical events are the most significant force in the project cycle, and ultimately they drive the length and cost of the project.

The beginning and the end of the cycle deals with the user's requirements and the user's satisfaction, respectively. These are the highest

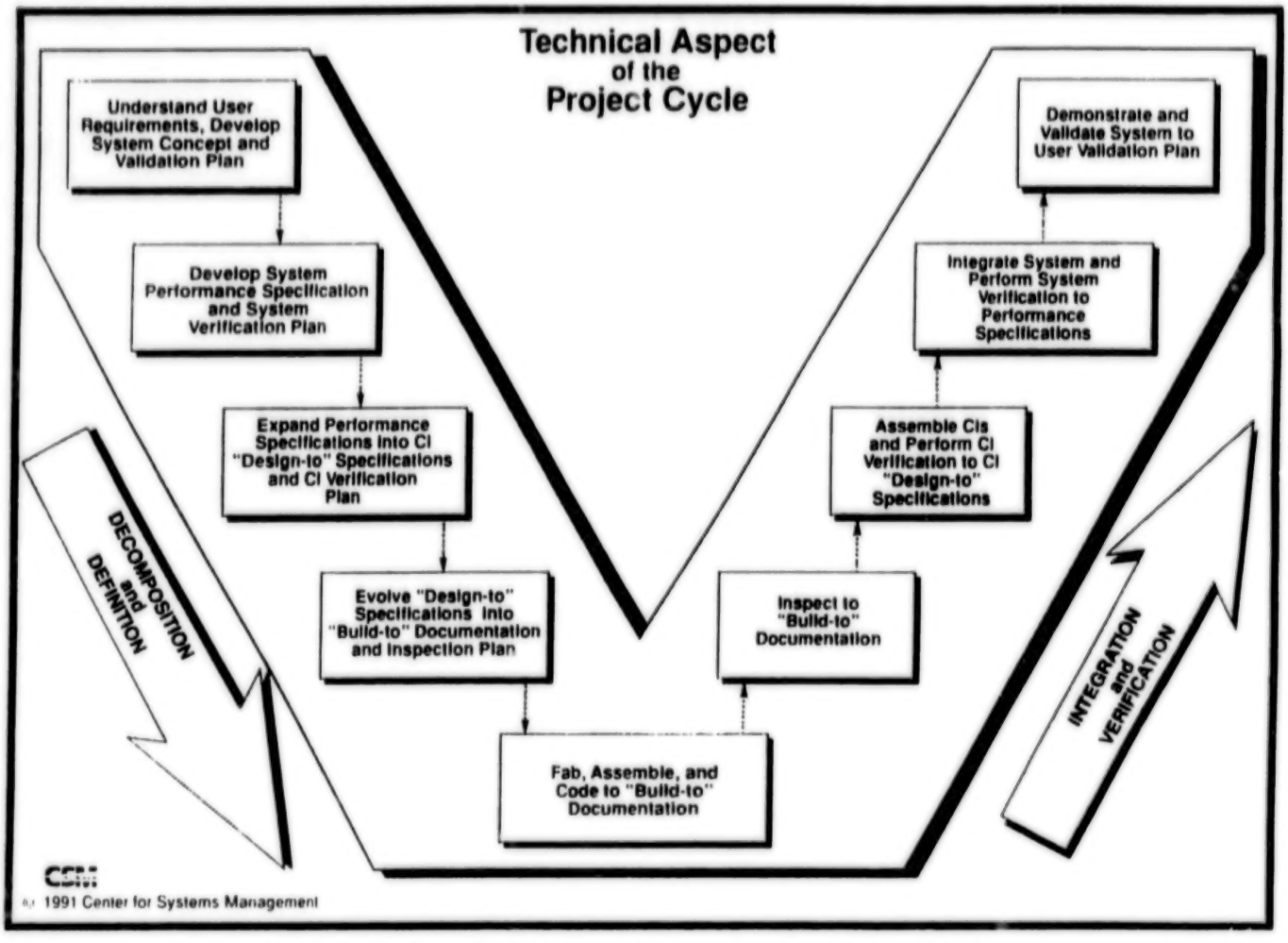

Technical Aspect
of the
Project Cycle
Understand User Requirements, Develop System Concept and Validation Plan
Develop System Performance Specification and System Verification Plan
Expand Performance Specifications into CI "Design-to" Specifications and CI Verification Plan
Evolve "Design-to" Specifications into "Build-to" Documentation and Inspection Plan
Fab, Assemble, and Code to "Build-to" Documentation
Inspect to "Build-to" Documentation
Assemble CIs and Perform CI Verification to CI "Design-to" Specifications
Integrate System and Perform System Verification to Performance Specifications
Demonstrate and Validate System to User Validation Plan
DECOMPOSITION and DEFINITION
INTEGRATION and VERIFICATION
CSM
© 1991 Center for Systems Management

Figure 2 - Overview of the Technical Aspect of the Project Cycle

levels of the "V." In the center of the cycle, at Critical Design Review (CDR), the events of the project are at the lowest level, dealing with hardware and software process details such as fastening, bonding, and coding. The left side of the "V," descending from the highest point to the lowest point, is defined as Decomposition and Definition. The right side of the "V", ascending to the fully operational system, is called Integration and Verification. System engineering is responsible for the technical management of the entire "V."

Typically, the upper portion of both sides of the "V" is managed by the government, with contractor participation. The center level of the "V" is managed by the contractor's systems engineers, with design engineering participation and government oversight. The lower portion of the "V" is managed by the contractor's design engineers, with oversight by the contractor's systems engineers.

Only the core of the "V" is presented in Figure 2. The process illustrated here is similar to the traditional waterfall model of system decomposition and integration. However, this model provides improvement in the understanding process. Detailed hardware, software and operational analysis is recommended at each step in the decomposition to assess solution feasibility and risk, and to provide necessary data to select between various options (see Figure 3). As the project progresses from one step in the "V" to the next, only the decisions on the core are put under configuration management.

Off-core details are illustrated by the process of requirements flowing down to successively

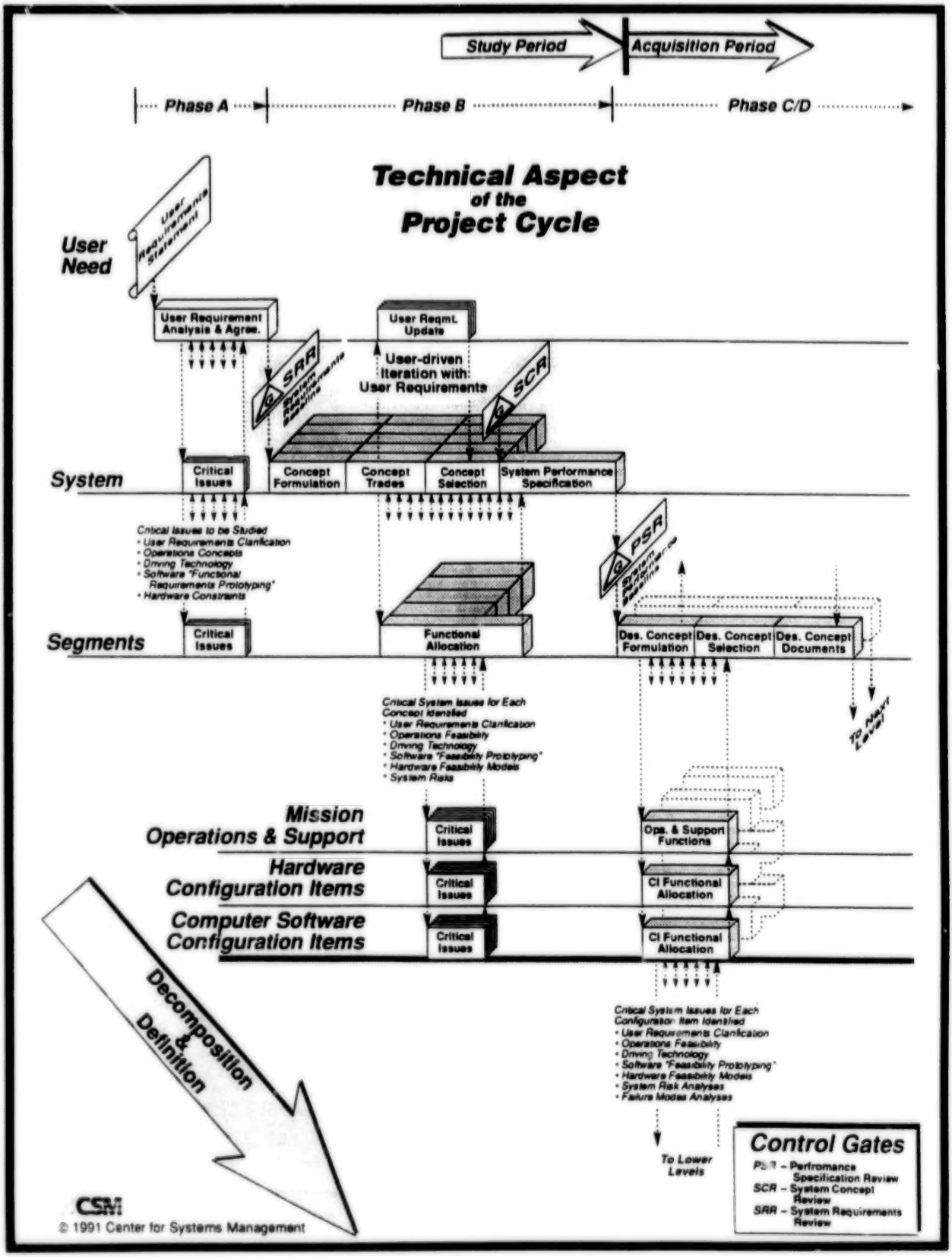


Figure 3 - Details of the Technical Aspect of the Project Cycle (Partial View)

BEST COPY AVAILABLE

lower levels, performing trade-off analyses to determine the best approach at each level (as depicted in Figure 3). This progressive and iterative process is repeated until the lowest level decisions have been made with valid rationale, all traceable to the original user requirements. Management of the Decomposition and Definition process demands both requirements traceability and baseline configuration management. The management of Integration and Verification requires compliance verification and full accountability of all specified requirements. Systems engineering is responsible for this management.

As the project proceeds through the "V," it progresses in time and maturity. The maturity is measured by the evolving technical baseline, which is progressively placed under formal configuration control by the government project manager.

At the beginning of the "V," the approved baseline is the user's agreed upon requirements. At Full Scale Development (Phase C/D contract award), the approved baseline is the System Performance Specification. At PDR (Preliminary Design Review), the approved baseline becomes the approved "Design-to" specifications. At CDR (Critical Design Review), the approved baseline becomes the "Build-to" documentation. Baseline evolution and approval continues throughout the project cycle.

Project management is the most complicated of all management processes. It encompasses detailed sets of interrelated activities that involve many different specialty disciplines. These include funding, contracting, systems engineering, design engineering, production, quality, procurement, systems acquisition, systems integration, systems verification, configuration control, subcontracting, and many others. The interactive complexity is so great that it is difficult for even the most experienced team to operate proactively and efficiently without drawing on a baseline project cycle as a reference starting point.

While there are those who proclaim that a defined project cycle inhibits the creativity of project participants, just the opposite is realized. By having defined a typical cycle that is tailored to the project and then further expanded into the strategic network and project plan, the project team is not distracted by day-to-day project activities. A defined process releases contributors to concentrate on content, rather than process.

A defined project cycle illustrates the generic budget, business and technical events required to be successful. The project cycle should be tailored to the type of project and is the skeleton around which the strategic and tactical approaches to the project can develop into a logical network. By having a defined process, the team is free to be innovative and, therefore, more successful.

Systems Engineering and Integration Management for Manned Spaceflight Programs

by Owen Morris

This paper is one in a series prepared for NASA under contract from the Jet Propulsion Laboratory. Although the papers were commissioned by the NASA Alumni League, which also provided editorial services, the opinions expressed in the paper belong solely to the author.

The development of systems engineering and program management in NASA manned space programs has grown in a largely uncoordinated manner over the last 30 years; however, the systems and practices that have been developed form a proven pattern for successfully integrating large technically complex programs executed in several geographical locations. This development has not been recorded in a comprehensive manner, and much of the reasoning behind the decisions made is not obvious.

Although there is no generally accepted definition of SE&I, for the purposes of this discussion systems engineering is defined as the interdisciplinary engineering that is necessary to achieve efficient definition and integration of program elements in a manner that meets the system-level requirements. Integration is defined as the activity necessary to develop and document the system's technical characteristics, including interface control requirements, resource reporting and analysis, system verification requirements and plans, and integration of the system elements into the program operational scenario.

This paper discusses the history of SE&I management of the overall program architecture, organizational structure, and the relationship of SE&I to other program organizational elements. A brief discussion of the method of executing the SE&I process, a summary of some of the major lessons learned, and identification of things that have proven successful are included.

History

NASA, then the National Advisory Committee for Aeronautics (NACA), participation in the management of major aerospace programs began shortly after World War II with the advent of the X-series research aircraft. In these projects, essentially all of the technical responsibility was delegated to one of the NACA Centers. At this time, the Centers were primarily expert in the technical areas being explored (i.e., aerodynamics, stability, control, and structures) but did not have experts in the development of hardware. Accordingly, NACA entered into agreements with the Air Force or Navy to manage the actual development of the aircraft, while the NACA Centers focused their direction on the technical requirements and performance characteristics to be demonstrated by the aircraft. The contractor's responsibility was similar to that for the development of any aircraft, and the contractor usually furnished test pilots for early demonstration flights.

With the formation of NASA and the start of major manned space programs, it was necessary for NASA to develop the capability to manage complex development activities. Very little SE&I capability existed within the functional organizations of the NASA Centers. As a result, SE&I expertise was developed within each of the program offices. In particular, the Gemini program office was set up with autonomous capability to manage SE&I and direct the development contractor.

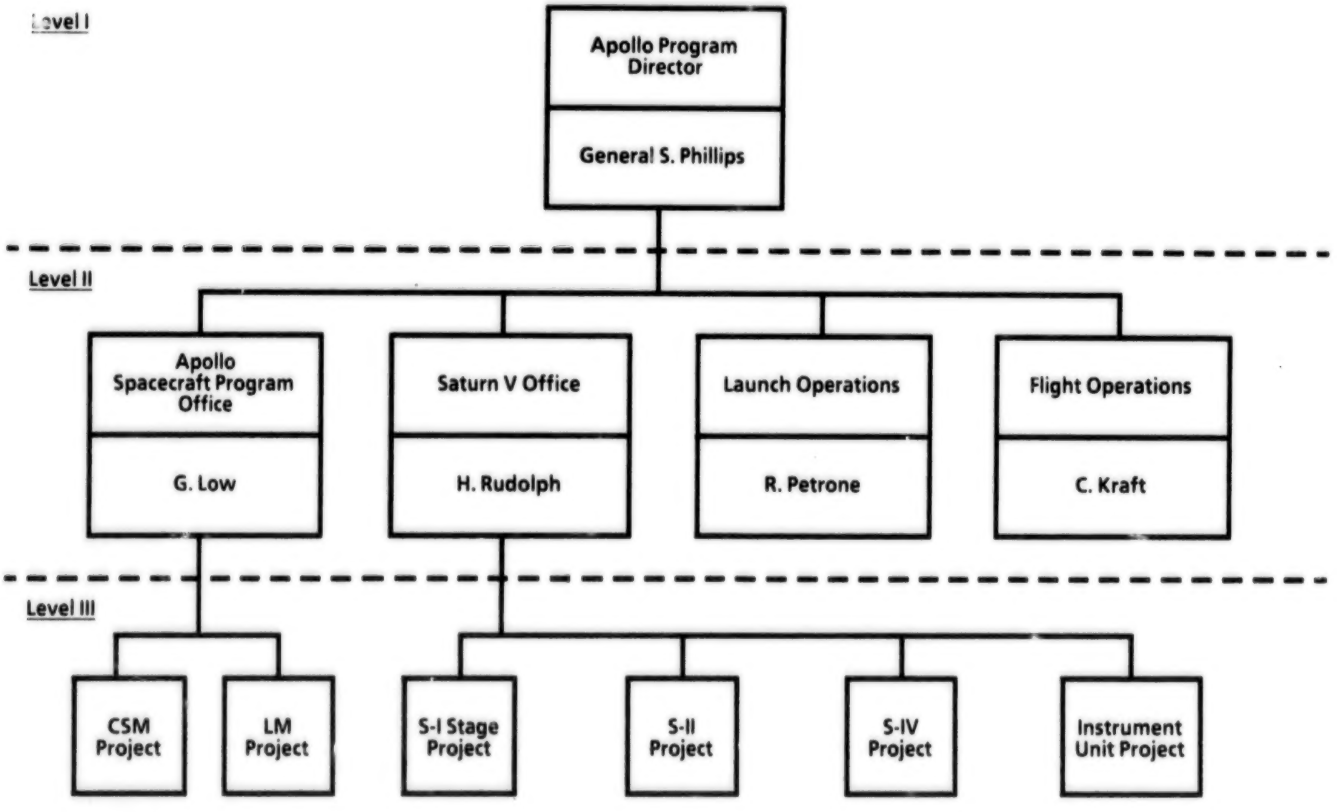
With the advent of the Apollo program, SE&I was again managed from the project offices at the development Centers. The project offices used specialized technical capability from the Center functional organizations and prime contractors and initiated the practice of hiring support contractors to assist in implementing SE&I.

After the Apollo I fire, a review committee was established to determine the cause of the fire and recommend modifications to the program. One of the recommendations made was that NASA acquire a technical integration and engineering support contractor to assist in accomplishing SE&I activity. The Washington program office selected Boeing as the contractor and managed the contract for this activity; however, a large portion of the manpower was located at the development Centers. The contractor's responsibilities included monitoring the development and operational activities at the Centers, forming integrated assessments of the activity, and making recommendations to the program director for improvements. As the program matured, the contract focus was changed, and the contractor provided a significant number of personnel to directly support the centers in SE&I and systems activities.

With the initiation of the Space Shuttle program and the adoption of the lead Center concept, it was decided to manage the Level II integration activity, including SE&I, by providing a small management core within the program office and using many of the Center's functional organizations to provide technical support in a matrix fashion. At the Johnson Space Center (JSC), the lead person from the functional organization was generally a branch head or an assistant division chief. Therefore, JSC had a relatively large staff to draw from to provide the specific technical expertise and the level of effort needed to accomplish a given task.

The Space Station Freedom program was started using the Space Shuttle program as a model. As the lead Center, JSC managed integration. Later, the Level II function was moved near Washington, D.C., under the deputy program director, and an independent contractor was brought in to assist the integration process. The Space Station Freedom program's management organization is discussed in more detail in the next section.

Figure 1 - Apollo Program Organization

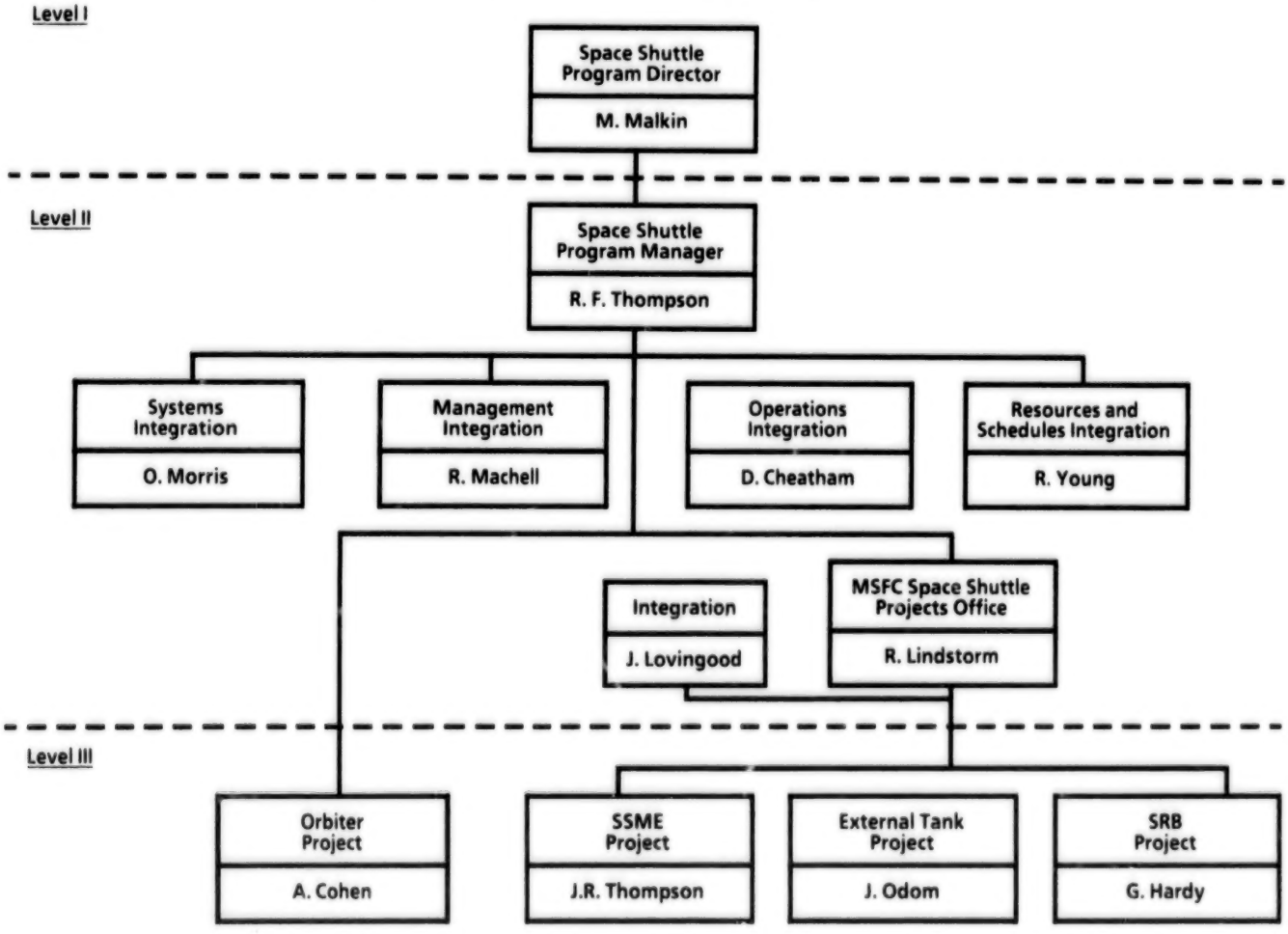


Program Management Organizational Structure

A single NASA Center largely managed early NASA manned space flight programs, which allowed for a relatively simple organizational structure to accomplish program integration. JSC, then called Manned Space Center (MSC), managed both developmental and flight operational aspects of the Mercury and Gemini programs with the checkout and preflight testing being performed by support elements at Cape Canaveral.

The Apollo program became organizationally more complex (see Figure 1). The spacecraft development was managed by JSC; the launch vehicle development by the Marshall Space Flight Center (MSFC); the prelaunch activities by the Kennedy Space Center (KSC), by then an independent NASA Center; and the flight operations by JSC. In all of these programs, the responsibility for the development of the flight hardware was delegated to the Centers, and the interfaces between projects were intentionally kept as simple as possible. The Washington office, under direction of the program director, was responsible for overall direction of the program including budgetary allocations, congressional relations, and management of development issues between the project offices at the different Centers. The actual integration activity (SE&I) was coordinated by a series of panels and working groups in which individuals from the Washington program office served as either chairperson or members, with the program director overseeing the activity. In the early programs (Mercury and Gemini), this activity was the responsibility of a single Center, and the Washington office was coordinated in an informal manner, but by the end of the Apollo program, the management of the panel and working group activity was relatively formal. In all of these programs the Center directors took an active part and personally felt responsible for the technical excellence of the work performed by their Centers. This in-

Figure 2 - Space Shuttle Program Organization



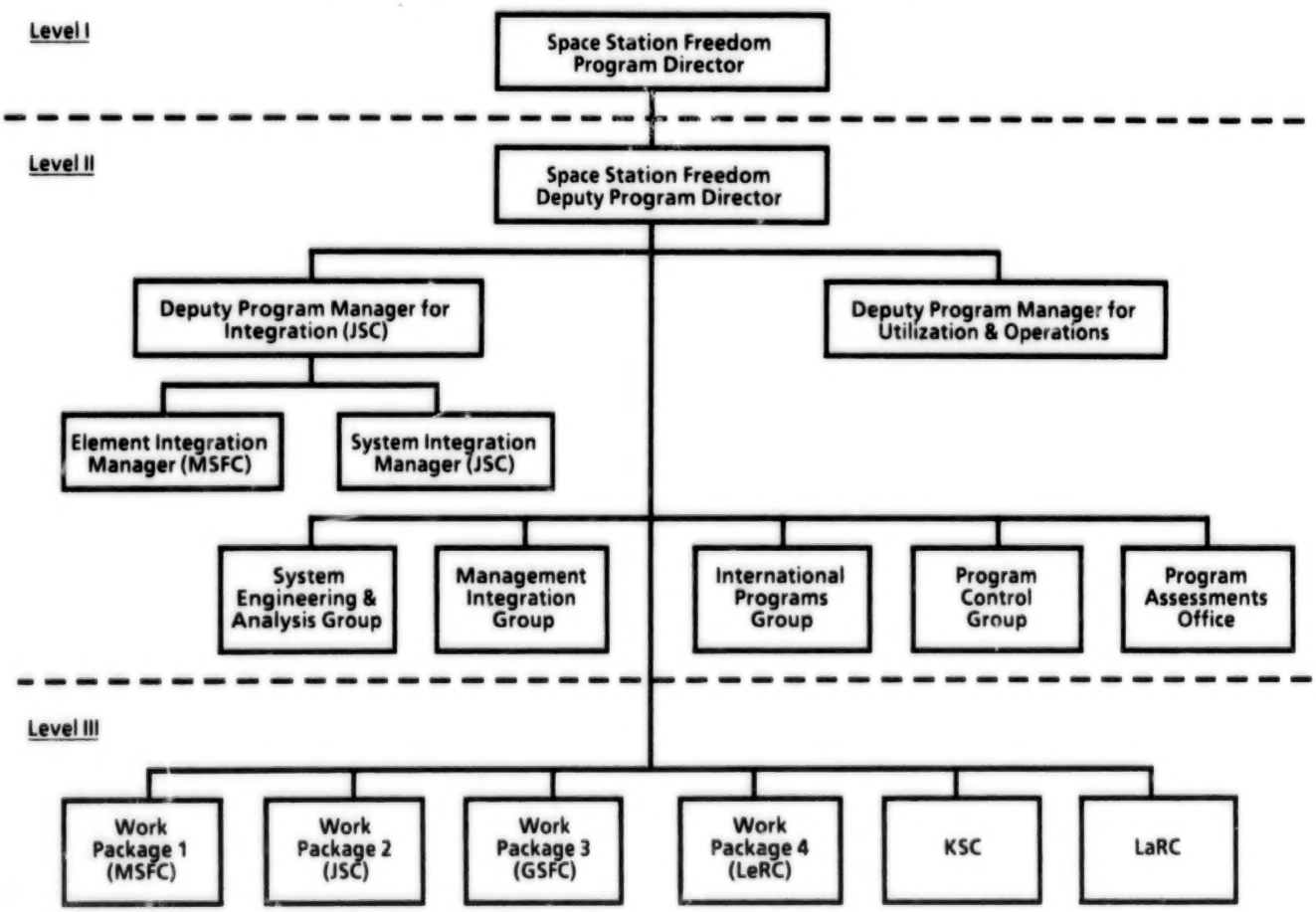
tercenter involvement was accomplished primarily through the management council and major program reviews where Center directors personally participated in major decisions.

In part of the Apollo program, the Washington office retained the responsibility for performing the SE&I activity with actual work being led by Bellcom, a division of Bell Laboratories. Ultimately, this approach was abandoned in part because much of the Center director's responsibility was lost, and an adversarial relationship between the program director and the Center organizations developed. The execution of the SE&I was returned to the Centers with management and coordination of intercenter activities achieved through the use of working groups, panels, and management reviews.

At the outset of the Space Shuttle program (see Figure 2), the management of SE&I was changed. Some of the more important changes were: adoption of the lead Center management concept, in which one of the participating Centers was delegated the management of program-level integration including SE&I activities; the adoption of a configuration with functional and physical interfaces of much greater complexity; and the employment of one of the major hardware development contractors as the integration support contractor. The complex interfaces made SE&I activity voluminous and involved and required the commitment of a larger percentage of the program resources to this activity.

The Space Station Freedom program was structured so that the interface activity between the work packages was even more complex than that of the Space Shuttle program. Initially, the lead Center approach to SE&I activity was adopted, but the implementation was not effective. As a result of recommendations made by study groups and the committee reviewing the Challenger accident, it was decided to transfer the responsibility for program integration activity, including SE&I, to the deputy program director in Reston, Virginia, and to bring on a con-

Figure 3 - Space Station Freedom Program Organization



tractor to provide program integration support (see Figure 3). Contractors having significant hardware development contracts were excluded from the contract competition. The first approach was to provide detailed management of SE&I activity by the Reston civil service personnel with the integration contractor providing support in executing the activity. Additionally, it was thought that much of the technical integration activity could be accomplished by having the work package contractors negotiate the definition and execution of much of the detailed integration process directly between themselves. This proved ineffective, however, because there was no clear lead responsibility and no clear way to resolve differences. As a result, because of the complexity of the program integration and the lack of in-depth backup capability, this management approach has not been completely effective.

Recently, it was decided to give the integration support contractor direct responsibility for the integration of the program but without authority to directly manage the work packages or their contractors. In an attempt to obtain more in-depth capability, the program director and deputy program director decided to execute the systems integration portion of the SE&I activity at two of the field centers with the deputy director for integration physically located at one of the Centers. Since these functions were still retained organizationally within the program office, they were under the control of the deputy program director and, at the same time, had the advantage of drawing from the technical capability residing at the Centers. Simultaneously, the integrating contractor's personnel at the Centers was materially increased in both responsibility and quantity.

Growing Program Complexity

One of the major factors that determines the efficiency of the integration of a program is the methodology used in delegating the engineering and development responsibilities to the project offices at the field Centers. It has been found that less complex organizational structures and simple interfaces are extremely important to allow efficient management of the SE&I activities. Each of NASA's manned space programs has been organizationally more complex than its predecessor and has had more complex interfaces. In both the Mercury and Gemini programs, the flight elements were divided into two parts, spacecraft and launch vehicle, and the physical and functional interfaces between the two were quite simple. The induced environmental interfaces were somewhat more complex but readily amenable to experimental and analytical determination.

The Apollo program involved a major increase in program complexity. The spacecraft was divided into two project offices while the launch vehicle was divided into four project offices. By assigning the four launch vehicle projects to the same development center (MSFC), the integration between launch vehicle stages could be accomplished at the Center level. Similarly, both spacecraft projects were assigned to one Center (JSC) for the same reason. The physical and functional interfaces between the spacecraft and launch vehicle, and hence between development Centers, was relatively simple. In a paper written in 1971 titled *What Made Apollo a Success*, George Low stated:

> *Another important design rule, which we have not discussed as often as we should, reads: Minimize functional interfaces between complex pieces of hardware. Examples in Apollo include the interfaces between the spacecraft and launch vehicle and between the command module and the lunar module. Only some 100 wires link the Saturn launch vehicle and the Apollo spacecraft, and most of these have to do with the emergency detection system. The reason that this number could not be even smaller is twofold: redundant circuits are employed, and the electrical power always comes from the module or stage where a function is to be performed. For example, the closing of relays in the launch vehicle could, in an automatic abort mode, fire the spacecraft escape motor. But the electrical power to do this, by design, originates in the spacecraft batteries. The main point is that a single man can fully understand this interface and can cope with all the effects of a change on either side of the in-*

terface. If there had been 10 times as many wires, it probably would have taken a hundred (or a thousand?) times as many people to handle the interface.

However, the operational complexity of the Apollo vehicle demanded a more extensive integration activity between the Centers, and for the first time posed the problem of accomplishing detailed technical coordination between Centers.

One of the basic tenets of the Space Shuttle program was to have an integrated vehicle that would recover the most expensive elements of the system for reuse. This led to a design concept that placed a great majority of the electronics and major components of the main propulsion systems in the orbiter. This design concept led to very large increases in interface complexity between the program elements and, more importantly, between development Centers. For instance, the number of electrical wires running between the external tank and the orbiter was more than an order of magnitude greater than between the spacecraft and launch vehicle of Apollo, and for the first item, major fluid systems ran across the interfaces. This represented a formidable increase in the effort required to successfully accomplish the SE&I activity. As previously noted, the new program management structure, shown in Figure 1, was adopted to accommodate the increase. The accomplishment of program level SE&I was given to a "lead Center." The program director at headquarters was still responsible for program budgetary control, Congressional relations and a technical staff sufficient to assure that the program technical activity was being properly implemented. At JSC, which was the lead Center for the Space Shuttle program, a Level II program office was established totally separate from the Level III orbiter project office, located at the same Center.

The development of the flight hardware was delegated to four project offices with the orbiter office located at JSC, as mentioned above, and the other three, the Space Shuttle main engine office, the external tank office, and solid rocket booster office, located at MSFC. In addition to the hardware development project offices, a prelaunch processing office was formed at KSC. All of the project offices reported to the Level II program manager for all programmatic direction except budget allocation, which was retained by the program director at headquarters.

The SE&I activity was delegated to the Systems Integration Office located within the JSC Level II Office. The orbiter contractor, Rockwell International, was selected to be the integration support contractor, but to increase objectivity, the integration activity was made a separate exhibit to the contract and technical direction was delegated to the Level II Systems Integration Office. The MSFC Space Shuttle Project Office appointed an integration manager to manage the integration of the Marshall Space Shuttle Projects and to serve as the primary interface to the Level II Systems Integration Office.

The flight hardware developmental delegation of the Space Station Freedom program was formulated in an even more complex manner (see Figure 4). End-to-end developmental responsibility for each of the major functional systems was delegated to one of four project offices called work package offices; the responsibility for assembling and delivering the flight hardware was broken down by launch elements, again assigned to one of the work package offices. Each of these launch elements incorporated components of most of the distributed systems, necessitating the transfer of an extremely large number of hardware and software items between work packages prior to their delivery to the government. This resulted in another major increase in the complexity of the program-level SE&I process and directly contributed to the difficulty of implementing a satisfactory SE&I process in the Space Station Freedom program.

SE&I Scenario

As a program develops from concept to operational status, the characteristics of the SE&I activity vary greatly. Early in the program, conceptual stage SE&I is intimately involved in defining systems that will meet the overall program objectives and in evaluating the

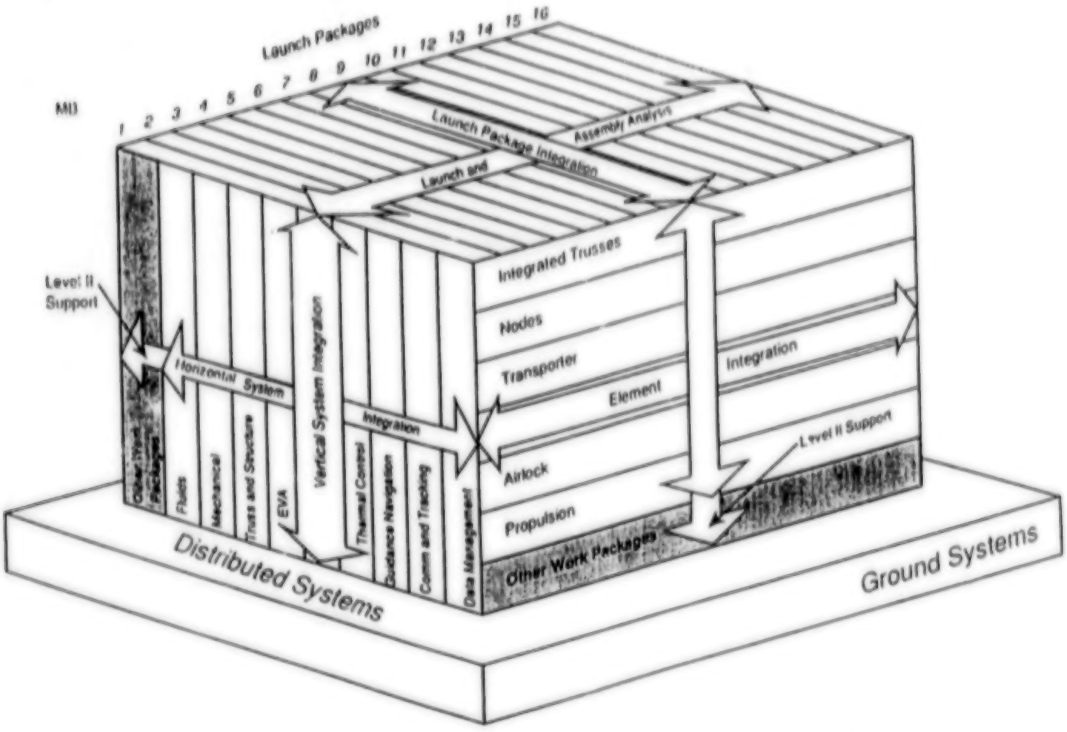


Figure 4 - Space Station Freedom Integration Activities

relative merits of each. This is usually accomplished in NASA manned programs by the civil service organizations, often in concert with Phase A/B contracts with industry.

After the general systems specification has been developed and a detailed evaluation of system concepts completed, SE&I provides a lead in the preparation of the procurement specifications for the Phase C/D activity and is usually directly involved in the source selection process. After award of the Phase C/D contracts and final selection of the design approach chosen for implementation, SE&I is responsible for preparing system level technical specifications, which define the performance requirements to be satisfied by each of the major program elements.

SE&I then develops the system characterization process to be used (discussed in more detail later) and starts an initial analysis cycle. The results of this cycle are extremely important in verifying the validity of the system technical specifications and providing a technical basis for conducting the Program Requirements Review (PRR). After completion of the PRR and updating of the technical specifications, SE&I starts the definition of the interface control document tree and the initial drafts of the documents. Another system characterization cycle is started based on the updated specifications and the hardware/software concepts chosen to assess the adequacy of the proposed preliminary design approach.

By this time in the program, the ad hoc organizational structure should be well in place and functioning on a routine basis. The communication and management overview provided by this structure of working groups, panels, and reviews is central to accomplishing horizontal integration among the project offices and is discussed in more detail in a later section.

In preparation for the preliminary design review (PDR), SE&I defines the minimum content required in the PDR data packages and is responsible for preparing system-level documents supporting the Integrated System PDR. During the PDR process, SE&I representatives participate in the project-level reviews with particular emphasis on the compliance of the project to the system-level requirements. During the integrated system PDR, emphasis is placed on assuring that the preliminary designs meet the operational requirements of the

program. The SE&I organization is intimately involved with the evaluation and disposition of review item discrepancies (RIDS) that are submitted during the review.

As a result of the PDR process, changes to the requirements and modifications to the preliminary design of the elements are incorporated. A new characterization cycle is then initiated to evaluate the compatibility between the modified requirements and proposed system capabilities. At this time, the drafts of the interface control documents are expanded and quantitative detail added to assure that they are mature enough to become baseline requirements in the program. This maturation process inevitably adds a significant number of changes to the baseline.

In a similar manner, the verification plans of the elements and the integrated system are refined and baselined. The responsibility for executing the test and analysis required by the integrated system verification plan is delegated to appropriate organizations who then prepare detailed plans for accomplishing the assigned portions of the verification.

Detailed mission operational scenarios and timelines are prepared by the operations organizations, and the operations and SE&I organizations jointly conduct an analysis of the system capabilities to support the scenarios. Concurrently, the acceptance test and prelaunch operations requirements and plans are prepared and delegated for execution.

In preparation for the critical design review (CDR), another system characterization cycle is performed based upon the detailed design of the elements. This cycle typically uses mature models to synthesize the hardware and software systems and also incorporates the results of tests performed to that time. SE&I participates in the conduct of the CDR in a manner similar to that of the PDR. After completion of the CDR, the system requirements and design changes resulting from the CDR are incorporated into the documentation, and another complete or partial system characterization cycle is performed to validate the decisions made during CDR.

After CDR, the primary activity of the SE&I organization is to analyze test results and conduct analysis to verify the capability of the system that is being manufactured. Particular emphasis is given to verifying the interface characteristics of the elements as defined by the interface control documents. This activity directly supports the preparation for the design certification review (DCR) and provides interface information necessary to allow acceptance of the system hardware and software by the government.

The DCR is conducted similar to the PDR and CDR but addresses the as-built hardware and software. Successful completion of the DCR certifies the acceptability of the as-built elements and the ability to be integrated into an overall system that will satisfy the initial program operations requirements. Final operational certification of the system is obtained by a combination of the DCR process and analysis of information obtained during early flight operation of the system.

SE&I organization participation throughout the program development cycle provides them a unique capability to support operational planning and real time operations. SE&I is the repository of corporate knowledge of the details of the system capability, which is vital to the effective and efficient operation of the system.

Relationship of SE&I to Other Program Functions

To effectively accomplish the SE&I task, the SE&I management organization must maintain good communications and obtain the support of other program office organizations. Some of the more important interactions are discussed below.

Configuration Management

The interaction between SE&I and configuration management is particularly strong. As the developers and keepers of the systems specifications, SE&I has an interface with the configuration management function that is extremely active throughout the life of the program. The SE&I office recommends the

baselining of the technical requirements as they become sufficiently mature and then serves as the office of primary responsibility for defining and evaluating most of the proposed changes to this baseline. The SE&I office, after proper coordination throughout the integration function, also recommends the processing of non-controversial changes outside of the formal control board meetings, where appropriate. This results in significantly reducing the board's workload and conserves the time of the key managers who are members of the Change Control Board. Significant issues are referred to the board, and the SE&I office presents its analysis of the issues involved and makes appropriate recommendations.

Program Control

SE&I supports the program control function in the development of program schedules and budgets. The key to making this support effective is the use of SE&I logic networks and estimates of the manpower required to accomplish activities. Because of its interdisciplinary nature, SE&I can assist in planning activities in many program areas.

Early in the program, SE&I helps define the content and schedule milestones for each of the projects so the coherent development of project-level schedules and cost estimates can be achieved. In addition to supporting program control, SE&I provides program control with the engineering master schedules (EMS) and associated budget estimates for incorporation in the overall schedule and budget system. SE&I also works with program control in the planning of major program reviews, provides technical leadership during the conduct of the reviews, and frequently chairs the screening groups and preboards.

Operations

In all of the NASA manned space programs to date, the SE&I function has been managed in a different organization from the operations definition and planning function. Although this is undoubtedly the best choice in the later phases of the program, it may result in a less thorough incorporation of operational requirements in the systems specifications and other SE&I products early in the program. It may be desirable to consider combining the management of SE&I and operations in the same office early in the program and then separating them at a later time, such as completion of the predesign review (PDR). The stated reason for separating the functions in the past has been that they serve as a check-in-balance on each other; however; this causes disconnects in the detailed interfaces between the two functions.

SR&QA

The interactions between SE&I and the System Reliability and Quality Assurance (SR&QA) functions depends on how the delegation of responsibility for executing the program is approached. If a large part of the SR&QA activity is accomplished within the SR&QA organization, then the interface with SE&I is mostly that of using SE&I as a reservoir of information or to perform specific tasks as requested by SR&QA. However, if the SR&QA office is responsible for setting the requirements for the SR&QA activities and evaluating the outcome while other organizations such as SE&I are delegated the responsibility for executing the work, then the interface becomes one of SR&QA defining and obtaining baseline approval of task requirements, monitoring execution of the task by SE&I, and evaluating the results to assure satisfactory achievement.

The former mode of operation was exemplified during early portions of the Apollo program, where the SR&QA activities were largely accomplished within the SR&QA office using basic engineering information obtained from SE&I and other program organizational offices. Later in the Apollo program, the second mode of operation was adopted, in which engineering offices, primarily SE&I, actually performed the work and made a first-level analysis prior to formally transmitting the results to SR&QA for authentication. This latter mode of operation was felt to be more effective primarily because problems and discrepancies were often discovered by the originating engineering office and corrected even before the task was completed.

SE&I Execution

Many techniques have been developed in past NASA manned programs that have proven effective and have become an integral part of implementing SE&I activities. The following paragraphs describe some of the more important techniques to assist those planning and implementing new programs.

Importance of SE&I Early in a Program

Comprehensive SE&I support is crucial in the early stages of complex programs to assist in determining the architecture to be used in delegating project responsibility. This is accomplished by dividing the program into the next lower level of management, the project offices. The primary outputs are comprehensive and clear program requirement specifications, identification of major programmatic interfaces, development of the ad hoc SE&I management structure, definition of operating concepts, and preparation of initial specifications for the hardware to be delegated to each project office.

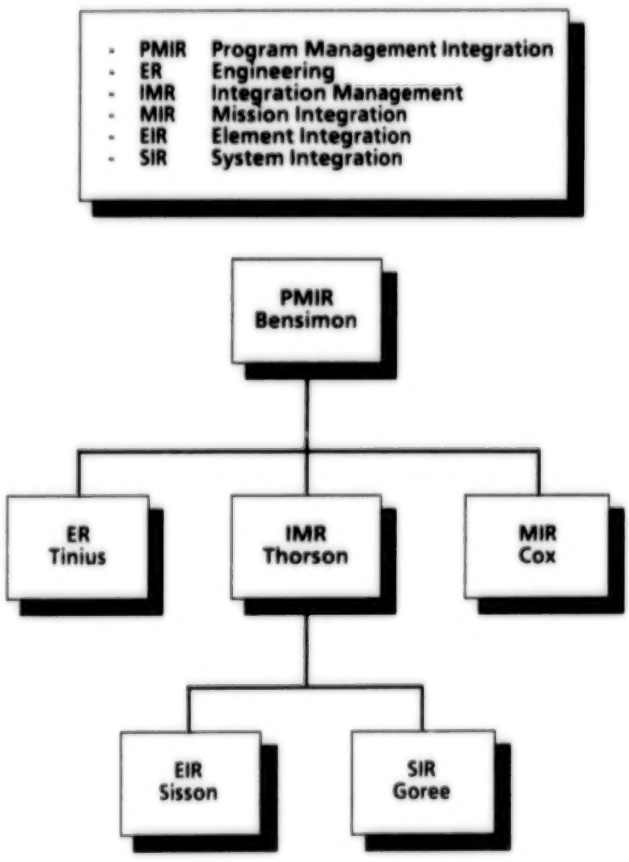
The SE&I organization is responsible for managing technical integration both vertically between different levels of the management organizational structure and horizontally across the organizations at each level. To efficiently achieve both dimensions of integration, it is necessary to develop logic diagrams of the major SE&I activities to be accomplished by each of the organizational elements and then to determine the interrelationships between them. By developing these diagrams and playing them against different organizational structures, it is possible to evaluate the proposed organizations in simple terms and easily define the interactions between the organizational elements, thus helping to choose the most efficient management structure. The importance of the logic diagrams will be discussed later.

Development and Use of Ad hoc Integration Structure

To manage the definition and implementation of the SE&I activities in manned space programs, NASA has developed an effective ad hoc organizational structure. The structure consists of a series of reviews, panels, and working groups that address the definition and management of integration functions throughout the program. Each of these organizations has membership representing all of the organizations interested in the particular integration function being managed. In the Space Station Freedom program, the working group structure is formed by technical disciplines and distributed systems, such as Guidance, Navigation and Control (GN&C), Robotics, and Loads and Dynamics. The panels are formed to address specific programmatic management areas (i.e., assembly requirements and stage definition, system design integration, and element design integration) that span a number of organizations. The reviews are formed to address relatively broad program areas as shown in Figure 5.

Each of these organizations is responsible for developing the integration plan in its area of responsibility, monitoring the execution of the tasks, identifying problem areas, and either re-

Figure 5 - Station Technical Review Structure 1990



solving them or submitting them to the overall program management structure for resolution. Many benefits result from the face-to-face meetings and interchange of information among peers in these organizations. Although these organizations by their nature do not perform work, the members, by working back through their functional organizations, greatly influence the work being accomplished in their particular areas of expertise. As rapport is developed between members, many potential problems and issues are identified and resolved without the need for referral to the formal management decision channels. In addition, the quality of the work materially improves. This ad hoc organizational structure also provides obvious places for program elements to present issues of any given nature for deliberation and resolution. All of the panels and working groups support each of the reviews as needed and submit their open issues to the most appropriate review for resolution.

The reviews address broad issues and serve as a communication channel between the panels and working groups. Since the reviews are broad and cover all of the panels and working groups, they provide an excellent way to assess and recommend activities that address the interdisciplinary aspects of the program.

Chairpeople of the panels and working groups are the best qualified individuals available in the particular discipline, and only secondary consideration is given to selecting a person from a specific organizational element. As a result of their recognized stature, the chairpeople provide leadership, which makes their recommendations and decisions more readily acceptable. The panels and working groups also request outside expertise when needed; such outside inputs are filtered by the panels and working groups prior to making a recommendation to the reviews or other management organizations.

Internal vs. Matrix SE&I Staffing

As already noted, SE&I activity was staffed and accomplished in different ways in the different NASA manned programs. At times, in the early manned space programs, the personnel required to accomplish the SE&I activity were assigned directly to the program and project offices. At other times, during the Apollo and Shuttle programs, the program office had only the people necessary to manage the SE&I activity, and most of the work was accomplished by technical experts assigned from the Center's functional organizations in a matrix fashion.

Although each had its advantages and disadvantages, the matrix approach in general appears to have had more advantages, one of the most important being that the manpower can be increased or decreased as needed by pulling support from the matrix organizations without requiring reassignment of the people involved. The primary disadvantage is that the leader of a particular area does not report functionally to the program or project office; therefore, the line of direction is not as strong, a factor that is inversely proportional to the working relationship between the organizations.

In the Space Shuttle program, this relationship and the matrix approach worked well. In other programs, the relationship was not as good and direction through the matrix was less effective. On occasion, program management appointed all panel and working group chairpeople from the program office staff, giving less regard to the personal qualifications of the individuals. This has led to a marked decrease in the stature of the ad hoc structure, which resulted in a lack of support from the functional organizations and a decrease in the quality of the integration activity and products. As in many areas of SE&I, effective implementation relies heavily on the quality of the leadership and the maintenance of free and open communications between the organizations involved.

Logic Networks

As the NASA manned space programs have become increasingly complex, it has become difficult to define the specific content and tasks needed to accomplish the SE&I function. Central to the development of a comprehensive SE&I plan is the development of detailed logic networks. These networks form the basis for planning, executing and evaluating SE&I activities.

As used in the Space Shuttle program, these logic networks covered all of the SE&I activities that had to be accomplished by all elements of the program organization. Thus, these networks were able to interrelate SE&I activities both vertically and horizontally throughout the program management structure. The basic summary logic networks were developed for the entire program duration to identify all major activities required as a function of time and were instrumental in developing cost and manpower forecasts for the entire duration of the program. Detailed logic networks were then prepared in the Shuttle program for 12 months, identifying in greater detail the specific activities to be accomplished by each organizational element during that period. The networks were revised every six months to extend the detail planning horizon, and in addition, the summary networks were reviewed and modified as needed on an annual basis. The logic networks were a primary input to the development of the engineering master schedules discussed next.

Engineering Master Schedules (EMS) and Associated Dictionary

The activities identified in the SE&I integration logic networks were then assigned to specific organizations for execution and presented as a schedule for each organization involved. By using a numbering system for the activities, a correlation between the logic network and the schedule could be easily provided. Preparation of the schedules allowed cost and manpower estimates to be prepared for each organization and provided an excellent means of updating and managing the activities in real time.

Associated with the engineering master schedule (EMS), a dictionary was prepared with an entry for each activity. Each entry identified all input information required to allow the accomplishment of the activity; described the contents of the products; and identified the primary user of each product, the scheduled completion date, and the person responsible for preparing the product. The EMS and the dictionary were the primary tools for defining and communicating SE&I activities throughout the entire program structure.

As would be expected, the basic content of the EMS changes character over the life of the program and accordingly requires a varying mix of technical capabilities as a function of time. Early in the program, the activities are primarily of a design nature and involve a large number of trade studies and the development of synthesis tools to be used in evaluating the capabilities of the proposed design. As the program matures and the design solidifies, the activities become more involved with exercising the system models, conducting tests, and analyzing data. As the flight phase approaches, the activities are predominated by operational considerations, including the development of operational data books, mission requirements, certification of system readiness, and support of mission planning and real time mission operations.

System Characterization Process

A major SE&I activity throughout the program life span is the assessment of the capability of the system to meet specified requirements. In the NASA manned space program, this has been accomplished primarily by synthesizing the vehicle characterizations in the form of either models or simulations and then developing detailed performance characterizations by exercising the models against selected mission timelines and significant mission events.

The methodology used in performing the system synthesis is central to the development of the logic networks and schedules described earlier. An examination of the system usually reveals scenarios useful in conducting the overall system evaluation, and after selecting the most desirable scenario, it is used to form the nucleus of the overall SE&I logic. In the Space Shuttle program, the scenario chosen was (1) developing the necessary models and simulations, (2) determining the structural modal characteristics, (3) determining the loads on each of the system elements, and (4) performing stress analysis of the system when subjected to these loads. Using this scenario it was relatively easy to define and interrelate the SE&I activities of other disciplines, such as GN&C, propulsion, and thermal, among others. After definition of all of the required ac-

the models to be used, the mission events to be analyzed, and a definition of the configuration to be used. The sequence described above formed an analysis cycle of a specific configuration subjected to specific operational requirements and, in the Shuttle program, was termed an integrated vehicle baseline characterization cycle (IVBC). In this article, the capability assessment is referred to as a system characterization cycle. As previously described in the SE&I scenario, several characterization cycles are needed during the life of the program. As the program matures, the cycles are characterized by having additional synthesis detail, more definitive configuration information, and better operational information.

At the completion of each of the characterization cycles, system deficiencies are identified and modifications to either the system specifications or the requirements are made. For program management purposes, it is usually convenient to schedule the completion of one of the characterization cycles to occur just prior to each of the major program level review milestones.

Program Reviews

SE&I has a large input to each of the program-level reviews, such as system requirements review, predesign review, critical design review, design certification review, and flight readiness reviews. As mentioned above, completion of one of the system characterization cycles is an excellent indicator of whether the system design meets the specified requirements, and the engineering master schedule gives a graphic representation of the integration progress being achieved. Reports produced by the SE&I activity—such as resource allocation status and margins interface control document status, design reference mission maturity, and system operational data books—give a good indication of the maturity of the element participation in the system-level SE&I process.

Design Reference Missions (DRM)

Most of the manned space programs had to be capable of performing a relatively large number of diverse missions, and the specifications are written in a manner to provide hardware and software systems and elements that are flexible enough to satisfy all of the missions. For analytical purposes, however, it is convenient to define and adopt one or more design reference missions (DRMs) that stress all of the system's capabilities to a significant extent. The DRMs are used as the primary mission requirements in the system characterization cycles, and in evaluating the ability to meet performance specifications. In addition to evaluating the baselined configuration against the DRMs, other specification requirements are evaluated by the accomplishment of specific analyses or tests as necessary.

The DRMs also allow the user community to evaluate whether the system is capable of meeting specific user needs and whether these needs are specifically in the system specifications. The DRM is also used by mission planners to determine the system's capability of performing any specific mission under consideration.

Verification

Verification plays a major role in program planning and in the ultimate cost of the system. Most of the verification is delegated to projects; however, SE&I is responsible for identifying overall verification requirements and specifically, identifying system-level verification test and simulations, which frequently require specialized facilities and significant amounts of system hardware and software. These system-level verification tests are frequently both complex and expensive, and planning for them needs to be started very early in the program. The system-level verification network is developed as an integral part of the program SE&I logic networks and baselined early in the program.

Final verification of some system requirements can only be accomplished in the real flight environment, and these are demonstrated in early operations before final certification of system operational capability is accomplished. It is also important to integrate the system-level verification planning and the operations planning to gain the maximum possible synergy between system verification and operational training.

In the manned space programs, all of the major system-level verification tests were assigned to program or functional organizational elements other than SE&I for implementation. This helps assure that the management of SE&I can remain objective in the evaluation of overall certification adequacy.

DCR Process

One of the more significant activities of SE&I is its role in the design certification of the system prior to the start of the flight operations and then again later, prior to committing the system to operating throughout the entire design envelope. SE&I is instrumental in setting the overall requirements for the DCR and is directly responsible for the system-level portion of the review. This process uses synthesis of the as-built vehicle hardware and software capabilities and results of tests and analysis. The results of the design certification process also form the basis for the system operational data books that are used in planning and conducting the operational phase of the program. The DCR requires that all system requirements be evaluated against all of the as-built system capabilities, and where possible, the system margins are quantified to assist the operations organization in planning and conducting flight operations.

ICD Development

As the program management organizational structure and the delegation of the responsibility for developing hardware and software are made, it is necessary to start the development of the interface control document (ICD) tree, which identifies each required ICD and the content to be presented. As previously noted, the division of program activities to minimize the number and complexity of interfaces has a strong influence on the overall program cost and the ability of the program to meet schedules. The early development of strawman ICD trees can greatly assist in optimizing the overall program management structure.

As the program progresses and the system configuration becomes better defined, the content of each ICD is developed in more detail and ICD working groups are formed to quantify the environmental, physical, functional, and operational characteristics in detail. In most of the manned programs, the ICDs have been baselined at a relatively early point in the program and have usually contained a large number of TBDs (to be determined). After baselining the ICDs, working groups then continue their work to arrive at specific values for each of the TBDs and to continually assess the adequacy of the ICDs as the design matures.

The ICDs are primary documents at each program review and provide a basis for evaluating the adequacy of the items being reviewed to satisfactorily function as part of the total system.

Program Management Organizational Structure

The efficiency of program management is greatly influenced by the organizational structure selected. Organizational structures that are compact and simple are essential to promote effective program management. Compactness is measured vertically by the number of levels of the program management organization and horizontally by the number of organizations at each level. Each organizational element added significantly increases the manpower and costs of achieving program integration, including SE&I. If each organizational element must interface with all others in the program, the number of interfaces increases rapidly as organizations are added. Adding management levels increases the complexity for delegating the execution of the program. This factor was evident to the Augustine Commission in their recent summary report *The Future of the U.S. Space Program,* in which they recommended that "multicenter projects be avoided wherever possible, but when this is not practical, a strong and independent project office reporting to headquarters be established near the Center having the principal share of the work for that project; and that this project office have a systems engineering staff and full budget authority."

In addition to keeping the management structure compact, it is also very important to select an

an architecture that divides the program into project offices so that the interfaces between projects are as simple as possible and that the delegation is all encompassing. In so far as possible, all of the deliverable hardware assigned to a given project should be the responsibility of that project to design and manufacture. In all of the manned programs prior to the Space Station, there was little transfer of hardware and software between projects with one exception, that being the development flight instrumentation in the Apollo program.

Early in the Apollo program, a decision was made to establish a civil service project office to develop, procure and deliver the specialized development flight instrumentation to the prime spacecraft contractors for installation and integration in the early spacecraft. Coordination of the very large volume of interface information required the development and maintenance of the complex bilateral schedules and support required.

The complexity of providing support after the transfer of instrumentation was a significant management problem throughout the entire time that the development flight instrument was used. In view of the extremely large number of hardware and software items that must be passed between work packages, it will be difficult for the Space Station Freedom program to develop, coordinate, and maintain all of the interface information required.

Objectivity in Management

To promote objectivity in managing SE&I, one of the basic ground rules in the Space Shuttle program was that the SE&I function would not be responsible for the development of any flight hardware or software products; thus they had no conflicting pressure to make their development job easier at the expense of another organization. It was found that any bias, either perceived or real, immediately brings the objectivity of management into question and rapidly destroys the confidence between organizational elements.

Need for Good Communication

The nature of SE&I is such that most of the program elements and many other agency organizations are involved in the execution of SE&I tasks. To facilitate accomplishment of the work, the importance of free and open communication cannot be overly stressed. One of the ways of accomplishing this is "to live in a glass house." All decisions and, of equal importance, the logic behind those decisions must be communicated to all parties involved if they are to understand their role and how it fits into the overall picture. All parties must feel that their inputs are included in the decision-making process.

This openness, and the accompanying feeling of vulnerability, is not welcomed and requires faith and confidence between the organizations involved. The fact that mistakes will be made must be accepted, and all organizations involved must constructively assist in correcting them. Frequent open meetings of the ad hoc organizational elements described above have proven to be an effective tool in developing rapport between peers and communicating information and decisions throughout the program structure. As noted earlier, however, such meetings become increasingly time-consuming and expensive as the complexity of the organizational structure is increased.

Importance of Margins

At the time programs are initiated, they are frequently sold on the basis of optimistic estimates of performance capability, cost, and schedules. This often results in reducing margins to low levels at program initiation and solving early program costs and schedule problems by reducing weight, power, and other resource margins. As a consequence, margins are reduced to zero or negative values early in the program, making it necessary to modify the program to either reduce requirements or introduce program changes that will re-establish positive margins.

The recovery of the margin inevitably leads to significantly higher ultimate program costs in both dollars and days. Minimum life cycle costs

are achieved by holding relatively large margins early in the program and then allowing them to be expended at a prudent rate during the program life cycle.

Things That Have Worked Well

In the management of the manned space programs' SE&I activities, several approaches have been particularly successful. Some of the more important, briefly summarized below, have been discussed previously in the paper but are readdressed here because of their assistance in the management of SE&I.

Ad hoc Organizations

The use of ad hoc organizations to coordinate SE&I activities has proven to be a valuable tool. The effectiveness of SE&I depends heavily on good communications between organizations and the assurance that a common approach to the implementation of SE&I is being taken by all organizational elements. This is difficult to accomplish using the normal program office organizations because they cannot directly address interorganizational communications and have difficulty in managing across organizational lines. The ad hoc organizational structure, on the other hand, is made up of specialists from each of the affected organizations, and their activities directly promote interorganizational communications. Using this technique, technical peers can plan and monitor the execution of specific SE&I activities. When a resolution cannot be reached within the ad hoc organizational structure, the issue is referred to the proper program management office.

Common Organizational Structure Within the Program and Project Offices

During the Apollo program, the program director decided to have all of the program management offices at both Level II and Level III adopt a standard organizational structure. Five offices reported to the program manager and to each project manager. This technique assured that the work breakdown structure was similar for all offices, that direct counterparts could be identified in each of the offices, and that budget allocations flowed down in a uniform and predictable manner. All of these features resulted in less cross-linking between organizations and made the required program management activity more rational and predictable. Although the specific office structure chosen would be different for each program, the concept of having uniformity between the Level II and Level III management offices should be considered for future programs.

System Characterization Cycles

Constructing the SE&I plan and identifying the required tasks is a very complex undertaking in large programs, and as previously described, it is best to meet the specified requirements. Analysis of the results reveals deficiencies and allows modifications to either the requirements or the system design to be identified, thus assuring an adequate margin of performance. Building on this core analysis cycle, it is relatively easy to plan the other SE&I tasks around it in a consistent manner, providing a complete characterization of the system capability.

Matrix Management Organizational Approach

The concept of staffing the program management office with a small number of people who serve as managers only and then augmenting their capability with personnel drawn from other Center organizations in a matrix fashion has significant advantages. Personnel can be brought in from the organizations only when they are actually needed, and the makeup of the technical capability can be changed as a function of time to satisfy programmatic needs. The quantity can be augmented to meet program needs, i.e., major program reviews; the personnel involved can be assured of a career path in their parent organizations; and the individuals involved can continually replenish their expertise by participating in the R&D activities in their parent organizations.

This mode of operation has been quite successful and has demonstrated several additional

attributes such as reducing friction and undesired competition between the program office and Center functional organizations, improving technical communications across programs being implemented simultaneously, and providing an efficient way of phasing the development program into an operational role. It is noteworthy that the assignment of program-level SE&I to a lead center, coupled with the execution of this assignment using Center functional organizations in a matrix fashion, allowed the program to take advantage of both the quality and quantity of technical expertise available throughout the Center.

Use of a Prime Development Contractor to Provide SE&I Support

In the Space Shuttle program, the SE&I support contractor was also the prime contractor for development of the Space Shuttle orbiter. Although there was considerable concern about the ability of the contractor to maintain objectivity in supporting SE&I, this concern was reduced to an acceptable level by separating the direction channels of the development and integration activity both within NASA and within the contractor's organization. The support contract was also set up with an award fee structure in which SE&I was responsible for providing inputs for the SE&I activities. There were many advantages to having this arrangement:

a) The integration personnel were familiar with one of the major program elements and did not need to become familiar with that element or the general program structure.

b) Expert technical specialists could be made available for both activities as needed.

c) Many of the synthesis tools required by both activities were similar, and frequently one model could be used for both purposes with only minor modifications.

d) Uniformity in approach assured ease of comparison of results from both project and program level activities.

Summary

The management of SE&I in NASA's manned space programs has developed over the last 30 years to integrate complex programs satisfactorily. Some of the approaches and techniques described in this paper may be helpful in integrating future programs. Careful consideration of the organizational structure and systems architecture at the start of the program will largely determine the level of effort required to accomplish the SE&I activity.

Shared Experiences from NASA Programs and Projects: 1975

by Frank Hoban

This paper summarizes the lessons learned from two workshops held at the National Academy of Sciences in 1975. The workshops were sponsored by NASA in conjunction with the National Academy of Engineering. Vince Johnson, former deputy administrator of the Office of Space Science and Applications, chaired the sessions. The National Academy of Engineering was represented by retired NASA executives Robert Gilruth and Abe Silverstein, retired USAF General King, and Sid Metsger of COMSAT.

The first workshop was held on February 24 and 25, 1975. The second workshop was held on June 3-4, 1975. Again, the National Academy of Sciences hosted the session. In order to provide more time for discussion, the number of projects to be covered was reduced from nine to six.

Orbiting Solar Observatory
Goddard Space Flight Center
Robert Pickard, Manager

The first project discussed was the Orbiting Solar Observatory-I (OSO-I). The OSO Project, dating back to 1959, consisted of a series of seven satellites prior to OSO-I. Ball Brothers had built all previous spacecraft; however, due to major changes, the I, J, and K spacecraft were competed, with the Hughes Aircraft Company the winner.

The primary objective of the OSO-I mission was to investigate the lower corona of the sun, the chromosphere, and the interface in the ultraviolet spectral region, to better understand the transport of energy from the photosphere into the corona. The secondary objective was to study solar X-rays and Earth-Sun relationships and the background component of cosmic X-rays. OSO-I consisted of one mission, using a 2,340-pound spacecraft with a corresponding payload of 827 pounds, carrying eight experiments. Orbital altitude was to be 320 miles circular at 33° inclination. Delta was the launch vehicle.

Prior to OSO-7, the costs of all previous spacecraft in the series were well below the $20 million level. OSO-7, the most expensive spacecraft of the series cost approximately $33 million; however, OSO-I costs were estimated at $58 million because of the complexity of the spacecraft and greater pointing accuracies. Spacecraft weights ranged from approximately 600 pounds for OSO 1-6 to 1098 pounds for OSO-7 and 2,340 pounds for OSO-I.

The project manager identified the following cost drivers:

- Control system complexity and precision.
- Stored command processor.
- Development of special integrated circuits.
- Inability of Government to maintain funding when needed.
- Experimenters building their hardware.

Elements of cost control exercised by the project were:

- Freezing the design.
- Descoping.
- Establishing cost ceilings on experiments and spacecraft.
- Use of financial management reporting on major contracts.

- Weekly manpower tracking at spacecraft-contractor.
- Frequent reviews with the contractor.

Recommendations:

(1) Use standard components and subsystems.

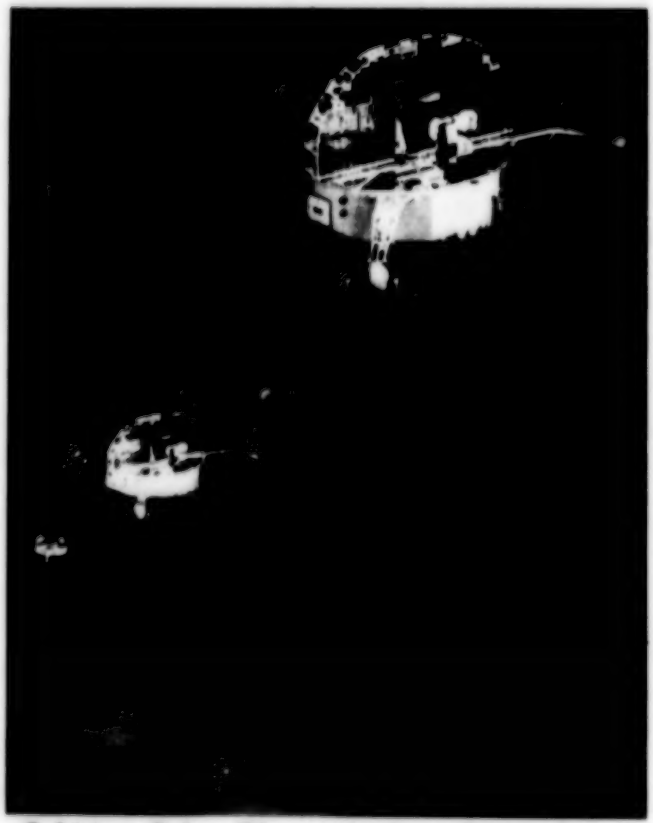
(2) Build experimenters' hardware to their specifications.

(3) Establish adequate funding contingencies.

(4) Freeze designs early and do not overdesign.

(5) Make subsystem engineers fully responsible for cost, schedule, and performance.

(6) Believe the cost model, not the proposal.



Orbiting Solar Observatories advanced our understanding of the Sun's structure and behavior, thus indicating the physical processes by which the Sun influences the Earth. This early NASA project was directed by the Physics and Astronomy program division.

Small Astronomy Satellite Project
Goddard Space Flight Center
Marjorie Townsend, Manager

The Small Astronomy Satellite (SAS) project consisted of three spacecraft: SAS-1, launched December 1970; SAS-2, launched November 1972; and SAS-3, launched May 1975. The philosophy of the SAS program was to build a basic spacecraft and attach an experiment to it. The SAS-3 mission objective was to survey the celestial sphere for sources radiating in the X-ray, gamma-ray, ultraviolet, and other spectral regions, both inside and outside of our galaxy. The spacecraft weighed approximately 262 pounds with a 169-pound experiment package. The orbit was a 300-mile circular equatorial. The launch vehicle was a Scout.

The main elements of SAS management were:

- Management is not by committee—one leader makes final decisions.
- Close teamwork by a small project team of high quality.
- Conservative design concepts.
- Control of workforce.
- Parallel design on critical items.
- Careful selection of parts and materials.
- Good communications with contractors.
- Selective testing program to minimize cost.
- Ability to predict problems.
- Good schedule control.

Recommendations for future projects:

(1) Start experiment development before spacecraft development.

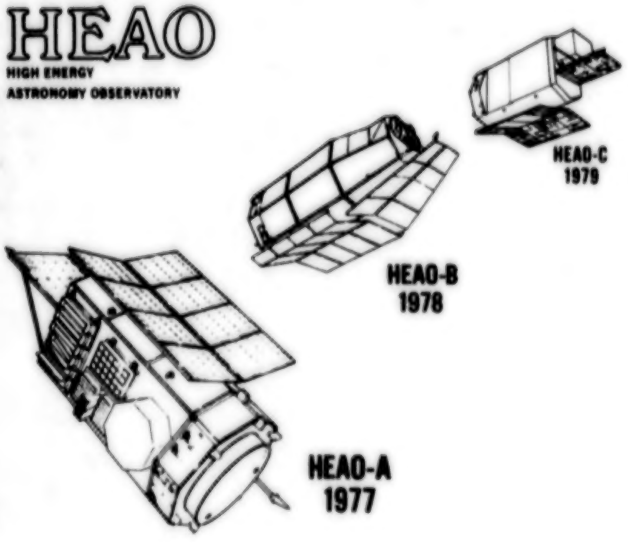
(2) Buy items requiring long lead times early.

(3) Implement configuration management after design phase; i.e., control changes.

(4) Have good business people on the project to help control costs and predict overruns.

(5) Work closely with contractor.

(6) Use existing design where practicable, but don't force-fit an old design.



HEAO Experiment Package
Goddard Space Flight Center
Ronald Browning, Manager

The next project discussed was the HEAO Experiment Package. The Marshall Space Flight Center (MSFC) was responsible for the management of the HEAO Project; however, the Goddard Space Flight Center (GSFC) provided two scientific experiments, a cosmic X-ray and a solid state spectrometer that were built in-house. The GSFC project office provided management of the hardware development and was the single point of contact with MSFC for all matters related to GSFC's HEAO experiments. The goals for the project office were to accomplish the program on schedule and within cost, incorporating maximum hardware commonality between experiments, and eliminating unnecessary redundancies in the design of each experiment.

Elements of management of the experiment package were:

- Development of experiments consistent with established GSFC in-house mode and acceptable to MSFC.
- Response to MSFC requirements.
- Coordination of project requirements.
- Configuration management.
- Systems engineering and design.
- Systems integration.
- Systems tests.
- Scheduling.
- Financial planning and monitoring.

Recommendations:

(1) Establish necessary resources early to meet other Center requirements.

(2) Thoroughly review experiments prior to Headquarters submission.

(3) Have better defined statements of work and specifications.

(4) Establish understanding at the begin-ning between Centers as to how the project will be managed and controlled.

(5) Keep spacecraft development more in parallel with experiment development, rather than one year behind.

Air Density/Hawkeye Project
Langley Research Center
Claude Coffee, Manager

The Hawkeye/Neutral Point Explorer Project was a 68-pound Scout-launched spacecraft built by the University of Iowa. The mission objectives were to study the topology of the magnetic

field at large radial distances over the Earth's North Polar Cap and the interaction of the solar winds with the geomagnetic field.

The University of Iowa was given total responsibility for project implementation with overall management responsibility at Langley. The university did an excellent job; the project came in ahead of schedule and under cost. Ball Brothers provided engineering support to the university. Unique features of this project included:

- A one-year Phase B study effort prior to project approval.
- An understanding with the university that funds were extremely tight, and overrun would not be funded by NASA.
- The university's use of contracted engineering services in areas in which the university had no expertise, and to augment key project technical personnel.
- Desire of principal investigators to launch at the optimum time (April through June).

The Dual Air Density Explorer Project (DAD) consisted of two satellites to be launched into coplanar polar orbits by a single Scout launch vehicle. The two satellites were a .76mm diameter spun aluminum sphere and a 3.66m diameter aluminum/mylar inflatable sphere. Each sphere contained a mass spectrometer furnished by the University of Minnesota.

The objective of the DAD mission was to study the vertical structure of the density, composition, and temperatures of the upper atmosphere. The two spheres were the instruments for inferring the atmospheric density, while the mass spectrometers measured the atmospheric composition. The molecular temperature was inferred by the change in vertical composition.

Project cost drivers identified were:

- Cost limitations resulted in an 11-month slip in schedule. The greatest impact was in-house manpower, resulting in increased institutional management charges.
- Institutional management system was Center-controlled with methodology changing from year to year.
- Project management must be critically aware of manpower loadings to hold down the institutional management changes.
- Problem solving by increasing in-house manpower tends to impact total project costs.
- Principal investigator did not establish firm cost estimates for data reduction and analysis.

Problems encountered were:

- Lack of early engineering support because of other in-house flight projects.
- Viking problems that impacted project manpower at various times.
- Inflation of sphere, coupled with the problems of procuring high-quality aluminum/mylar laminates materials for the inflatable satellite.

Recommendations:

(1) Extensive Phase B type studies should be performed for both the in-house and contracted effort. This means both manpower and funds availability.

(2) Develop "baseline" design specifications and interfaces early.

(3) Use fixed-price subcontracts.

(4) Be cost conscious and impress this on contractors.

(5) Avoid research and development after the project starts.

(6) Establish a realistic schedule.

(7) Develop a good relationship between project/contractor teams.

The Hawkeye Spacecraft is shown on the spin table during final systems tests before mating to the first five-stage version of the Scout rocket. Hawkeye-1 was launched June 3, 1974 to investigate the interaction of the solar wind with the Earth's magnetic field, with emphasis on the North Polar Cap. Hawkeye continued the University of Iowa's Injun series, which provided a comprehensive study of charged particles trapped in the Earth's magnetosphere.

Centaur D1 and Centaur Standard Shroud Projects
Lewis Research Center
Andrew Stofan, Manager

The original Centaur stage was designed in the late 1950s and by the middle 1960s it needed updating. Several small study efforts were conducted in the 1966-69 time frame. An initial development contract was awarded to Convair in September 1969 to design, develop, manufacture and deliver one improved Centaur D1 upper-stage qualified vehicle. Included in the contract were special test equipment, a ground station at launch complex 36, tooling, and flight software. The basic negotiated contract was for $24 million with a period of performance from September 1969 to April 1972. The contract, which included a cost-plus incentive fee/award fee, was unique for its time.

The contract was later modified to provide a D1 Titan proof flight vehicle and a D1A vehicle for Pioneer-G. The total contract cost increased to $50 million. The total program was completed 4.8 percent under cost, the end items were delivered on schedule and the D1A vehicle met all objectives. Although the D1T vehicle proof flight was terminated by a Centaur hydrogen boost pump failure, the validity of all the new developments was demonstrated.

The project manager detailed major project elements in the development shop organization:

- Simplified procedures and paperwork.
- Fewer formal documentation and reports (from 260 to 105).
- Segregation of program activities in controlled plant areas.
- Direct association of design engineers with fabrication, assembly, and test personnel.
- Simplified drawing system.
- Contractor program manager with overall responsibilities for technical, schedule, and financial aspects.
- Highly motivated government-contractor team with excellent communications.
- Government-contractor team uses identical controls:
  - Schedules by Statement of Work (SOW).
  - Financial data by SOW.
  - Technical requirements by SOW.
- Designation of contractor engineers for total SOW responsibility—technical, schedule, financial.

Other successful project management elements included:

- Task definition thoroughly understood.
- Cost definition based upon realistic goals with detailed backup rationale.
- Motivating contract features.
- Proper program management organization at NASA and contractor.
- Appropriate management systems and tools.

Studies of the Titan/Centaur launch vehicle indicated that a combined payload nose fairing and Centaur insulation system was desirable. Later studies defined the concept of the Centaur Standard shroud (CSS) to fulfill the study requirements. The Shroud was sized approximately 18.3m in length, 4.3m upper diameter and 3.35m lower diameter to accommodate the Viking payload and Centaur and Viking lengths. Requests for proposals were issued in July 1969. Lockheed Missiles and Space Company, Inc., was awarded the contract. Lockheed had extensive experience in building similar large shrouds for the Air Force and had a proven separation system. A cost-plus incentive fee/award fee contract was again used; however, this contract experienced a large cost overrun and cost growth. The major reasons for the growth were that the 4.3m constant diameter Lockheed design caused extensive Shroud/Centaur interface revisions and that the Viking Program slipped two years. The overrun was caused by contractor's military shroud program development problems, the contractor scrapping the "development shop" approach, extensive personnel turnover in manufacturing, and overhead and labor rate increases due to reduced business volume.

Technical results:

- CSS passed all qualification tests successfully and with relative ease. Only minor problems occurred with insulation and backup separation systems.
- CSS performed flawlessly on proof flight and Helios-A launches.
- All hardware was delivered on time and all major milestones were met.

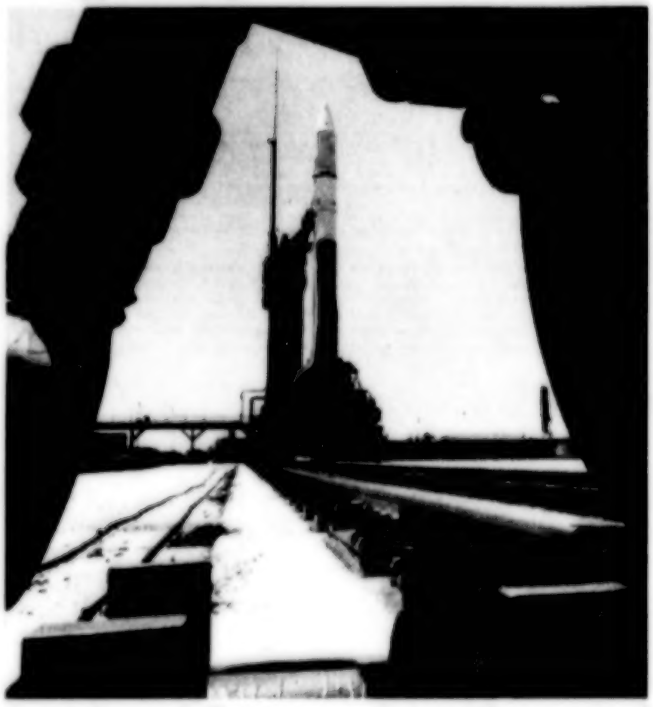
Recommendations:

(1) Contract should not be started with major inadequacies in the work statements.

(2) A "development shop" contractor organization is mandatory to control costs on contracts with a potential for engineering or schedule changes.

(3) Contractor top-level management attention and authority are vital in controlling expenditures of contractor organizations not under direct control of the project office.

(4) Defining sound interfaces between contractors is often the critical factor in controlling overall project costs, and is worthy of the utmost attention of contractor and NASA upper management.



An enhanced Centaur rocket with a resized shroud stands ready at Kennedy Space Center's complex 36 in 1978 to launch the Pioneer Venus Multiprobe, carrying four probes to enter the Venusian atmosphere.

Mariner Mars 71
Jet Propulsion Laboratory
Robert Parks

The final project discussed was Mariner Mars 71 managed by the Jet Propulsion Laboratory (JPL). The Mariner Mars 71 spacecraft weighed 2,266 pounds with an instrument package weight of 151 pounds. The primary mission objective was to study the dynamic characteristics and to provide broad area observations of the planet Mars from Martian orbit.

The project was formulated in the face of a threat that no new planetary programs would be approved unless attractive low-cost systems could be provided. During this period, both the Mars 71 Probe and the Voyager projects had been canceled.

A study of the Mariner Mars 71 launch opportunity revealed that it was the lowest energy year in the 15-year cycle and the Atlas Centaur could be used as the launch vehicle. The original approach was to use the Mariner Mars 69 science payload with no significant modifications. However, this approach was subsequently changed to include additional instrumentation, modifications to the Mariner Mars 69 instruments, and broader involvement of science investigators. These changes resulted in a cost increase from the initial estimate of $93 million to $106.3 million. JPL managed the project in the subsystem contracting mode.

Summary of major cost drivers:

- Inflation.
- Mission scope changes:
  - Science experiments.
  - Adaptive mode for mission operations.
  - Science data analysis expansion.

Experience with handling cost drivers:

- Inflation—per direction, initial cost estimate stated in 1968 dollars with no allowance for inflation.
- Unanticipated technical problems.
- Scope changes—additional science instrumentation.
- Costs partially offset by deleting third spacecraft.

Recommendations:

(1) Initial cost estimates should include an allowance for inflation.

(2) A definitive statement of science payload requirements, with an estimate of instrument development costs and their effects on spacecraft costs, is needed.

(3) Include some funding contingency to cover costs of unforeseeable problems.

(4) Standardize, wherever practical, on designs, components, and test procedures.

(5) Undertake block buys of identical hardware subsystems.

(6) Share mission operations costs associated with personnel and software.

Summary

These programs and projects—ranging in cost from $1 million to $2.5 billion—show not only the vast diversity of NASA activities but also the wide differences of opinion and strong, independent thinking on the part of NASA program and project managers. No two sets of cost drivers or sets of recommendations are identical, but a pattern does emerge. That pattern can best be summed up in one word: planning. Good plans make good projects. And good planning starts with the selection of well-trained, competent program and project management leaders and teams.

All too often, especially in the early days, program managers learned on the job. Experience is a good teacher, but there are other ways to learn. There is no logical reason why we must learn only from our mistakes when we can learn from the mistakes—as well as successes—of others. In this article, we have lists and lists of reminders and suggestions from program and project managers, many of whom have gone on to lead bigger programs within the agency and in industry. Their wisdom is valued and can be worked into the curriculum of any upcoming NASA project or program managers. Comparing and contrasting methods and techniques in the lists shows that while there is no one way to plan a program and manage it, some ways may be certainly better than others, and some are lessons learned, never to be repeated.

The following recommendations were made to the Deputy Administrator upon completion of the workshops:

- Initiate training for project personnel
- Hold periodic meetings with project personnel
- Prepare "lessons learned" reports at the completion of projects
- Establish independent cost review teams to verify estimated projects costs
- Establish an agency-wide piece parts purchase and qualification program
- Conduct a definitive reliability study
- Establish a policy regarding research and development in flight projects versus "enabling technology" under SR&T
- Initiate pre-project approval buys and block buys
- Establish and manage funding contingencies
- Consider cost-at-completion versus cost-per-FY for total cost management
- Define Headquarters role in project management

It is interesting to note that only the first recommendation was fully implemented and even it failed for a time. The other recommendations were well thought out and made excellent sense but there were no sponsors to carry them out.

A Strategy of Cost Control for Mariner Venus/Mercury '73

by John R. Biggs and Walter J. Downhower

The spacecraft NASA launched on November 3, 1973 to explore Venus and Mercury proved a notable success both in space and on the ground, as a development project. This article on the development points out management approaches and techniques that kept schedules and controlled costs, the intent being to stimulate thought about how to do the same with future spacecraft and payloads.

The Mariner Venus/Mercury '73 (MVM '73) project kept within its originally established goals for schedule, performance, and cost. Underlying this development success was the availability of the Mariner technology. But meeting the goals demanded management determination, planning, and discipline to make optimum use of state-of-the-art technology—on the part of people at NASA, JPL, and The Boeing Co. (the main contractor).

Pre-project Highlights

The earliest studies of the concept and scientific potential of a Venus/Mercury swing-by mission drew many to observe it could be the unique mission of the decade. It was the first to use a gravity-assist technique—taking advantage of an unusual planetary configuration existing in 1973. Using the gravitational field of Venus, it was possible to swing an Atlas-Centaur-launched spacecraft onto a flight path to Mercury. Exploration of Mercury otherwise would not have been possible without employing a much larger launch vehicle.

The 1968 Planetary Exploration Summer Study conducted by the National Academy of Sciences (NAS) Space Science Board (SSB) endorsed this mission. The SSB suggested that the mission be planned around a single launch to make best use of the science funds available to NASA.

Mission Objectives

The following mission objective, established by NASA following the Summer Study in 1968, did not change during the program's several years of design and development:

> *Primary*. During the 1973 opportunity, to conduct exploratory investigations of the planet Mercury's environment, atmosphere, surface, and body characteristics and to obtain environmental and atmospheric data from Venus during the flyby. First priority goes to Mercury investigations.
>
> *Secondary*. To perform interplanetary experiments while the spacecraft flies from Earth to Mercury, and to obtain experience with a gravity-assist mission.

JPL had long experience with planetary programs, but the opportunity for other Centers to participate in the program was not foreclosed. NASA's Goddard Space Flight Center (GSFC) had plans for a Planetary Explorer spacecraft potentially able to do the mission and its approach was sufficiently attractive to invite further study. During the remainder of 1968 and 1969, both GSFC and JPL studied their respective concepts; this early competition contributed to thoroughness of the early planning effort.

The Scientists

An innovative technique was used on MVM '73 to assure early involvement of the scientific community with mission definition and preliminary design. In past missions, no effective mechanism for the early detailed planning involvement of outside scientists had evolved, and selection of principal investigators had been withheld until the completion of mission-profile studies and early system determinations. By the

time the investigators were selected in those programs, many design features had already been established.

For MVM '73, selected scientists were invited to participate in the early mission planning. A group of scientists representing the several disciplines to be involved in the science payload was selected and formed into a Science Steering Group (SSG) in September 1969. The scientists influenced the early mission and spacecraft design, holding to a minimum conflict between mission constraints and science needs.

Based on the positive results from these planning efforts, MVM '73 was presented in the FY70 NASA budget as an Office of Space Science and Applications (OSSA) "new start" at a funding level of $3 million. An Authorization Conference Committee approved the project for inclusion in the FY70 authorization action, and funds were appropriated as requested. The scientific principal investigators were then selected in a normal fashion after project authorization.

Robert S. Kraemer, then head of planetary planning at NASA, pressed innovation in the early planning of MVM '73. Kraemer later moved to the post of planetary program director, with responsibility for implementing the project.

The "Low-cost" Attitude

The "low-cost" attitude, so evident in the management of MVM '73, developed early. The study teams were instructed to consider maximum use of established designs, residual hardware, and existing capabilities. Very strict financial constraints were factored into payload planning. The SSG was requested to consider minimum-cost experiments that would yield acceptable scientific data. The potential experiment proposers were advised to use existing designs for science instruments, to use flight-tested experiments wherever possible, and to consider modifications only for high-payoff options. They were also to limit quality assurance, reliability, and documentation requirements to that previously applied to prior successful similar instruments.

GSFC and JPL established the mission and spacecraft baseline, developed preliminary implementation plans incorporating the experiment approach being followed by the SSG, and made early cost estimates. JPL called on its extensive experience with Mariner spacecraft. Goddard proposed a spin-stabilized spacecraft of the Explorer class.

JPL proposed to commit to a fixed cost to do the MVM '73 mission in the system-contract mode. W.H. Pickering, JPL director, advised OSSA in December 1969 that JPL could and would undertake the project for a cost not to exceed $98 million.

The JPL Goal

After a full briefing on the approaches by GSFC and JPL (proposed science return, spacecraft configurations, management modes, manpower and cost projections), OSSA chose JPL. In a letter to Dr. Pickering, assigning project management to JPL, John E. Naugle, Associate Administrator for Space Science, made this comment regarding mission cost: "A major concern has been and remains to be the total runout cost of the project. I am sure you are aware of the cost history for which estimates have ranged from approximately $70 million to well over $100 million. It is mandatory that the project be accomplished for a total cost not exceeding the $98 million quoted in your letter and strong efforts should be taken to reduce this figure." This letter set the fundamental cost understanding between OSSA and JPL.

The "Work Package" Concept

JPL expertise in conducting flight projects predominantly involved obtaining spacecraft subsystems from industry thorough the JPL technical divisions with JPL accomplishing the spacecraft systems functions. The major challenge faced by JPL in the MVM '73 project was to utilize and adapt the fundamental JPL strengths to a system-contracting mode.

A JPL team suggested a "work package" concept as the best means to transition from the use of subsystem contractors to a systems contractor.

Appropriate elements of the JPL matrix organization prepared the work packages.

The Project Office exercised system technical direction, but the detailed definition, monitoring, and control of individual work units was performed by the appropriate JPL organizational element under the overall coordination of the JPL Project Office.

JPL also determined other factors important to implementing the project. It selected a cost contract with award fee. A specific JPL procurement group co-located with the Project Office would administer the system contract and other MVM '73-related ones. It was decided that the JPL in-house tasks should be given as much visibility and control as those of the system contractor. The constraint on resources dictated that all elements of the project, regardless of the performing organization, be monitored in the same detail, and the risks balanced across all portions of the project's activities.

PAD, Procedures and Payoff

The NASA project-approval process entails a basic contract or understanding between the Administrator and the responsible Program Associate Administrator: the Program Authorization Document (PAD). The initial PAD for the MVM '73 project was signed on February 27, 1970. The objectives, technical plan, major support interfaces, and procurement approach discussed in that PAD remained unchanged throughout the development.

The JPL approach strongly exercised the Mariner heritage. MVM '73 benefited not only from Mariner design derivation but also from residual hardware from past programs. The plan emphasized maximum use of existing designs, hardware and software. This approach saved perhaps 50 percent of design and development costs and perhaps 15 percent in hardware costs—a big payoff.

The Cutting Edge

The project team had lengthy discussions with JPL implementing organizations to identify the optimum way to meet cost constraints. Control of cost-at-completion became a basic concept stressed by both the JPL and Headquarters offices in an attempt to avoid the less-efficient, year-by-year funding controls often followed in projects. The MVM '73 project made it clear that each assigned work unit was the total responsibility of the cognizant division and that responsibility for determining the least costly way to do the work rested squarely with the division. For each potential increase in cost, something had to be cut back. The JPL divisions almost invariably proposed specific cuts concurrent with notification to the project office of potential cost increases.

Schedule Strategy

The schedule adopted for MVM '73 provided an unusually long period for advanced planning and deferred this start of major contracts. This approach, unprecedented in launch-critical planetary programs, may have been the single most important factor in meeting cost goals.

The added risk to the mission was offset by the increase in design time and better planning of the fabrication effort. The effect was to establish a "most cost-effective" approach. The greatest number of people worked on the project for the shortest period of time. (Axiom: the shorter the schedule, the less the cost.)

Once adopted as a project philosophy, delay in implementation was applied to all aspects of the project. The systems contract was delayed three months beyond the schedule considered minimal by many. Other subcontract work was released on a schedule that limited the work time to a prudent minimum. A "single thread" approach was followed in the spacecraft design where options were studied, one was adopted, and the work started without carrying parallel efforts. Mission operations work was held off beyond the schedule previously considered to be optimum. Flight operations crew training was held off as long as possible. And it worked! There were no major schedule slippages, no seriously late deliveries of equipment, and no extraordinary work-arounds.

"Do Only the Essential"

"Do Only the Essential" became a discipline among project participants. To challenge the need for each operation, each added procedure, each piece of special equipment, and each separate design, redundant feature or test became routine. If a function, part, or operation was determined to be needed, then the search went on to see if hardware was available from other projects, or if the process had been developed by someone else. If the part or process was not available, then there was an attempt to use available designs.

This discipline was not only applied by the JPL managers but by Boeing as well. The Boeing spacecraft program manager proved extremely resourceful in identifying short-cuts, reductions in paperwork, and unnecessary redundancy—the cost-type contract not withstanding. The list of hardware and effort saved through this effort is too lengthy to discuss here, but the savings extended to every area of the project effort.

One unusual saving is notable. The project team encouraged a local college, assisted by several other colleges and high schools, to produce the spacecraft models, which often cost more than $100,000. The project gained all the models required, the students and schools gained good experience from their work on an interesting task, and NASA saved dollars and encouraged local community interest and support.

Project Team

The most important ingredients to project success were the attitudes and skills of the people assigned to manage it. JPL's experience in dealing with a system contractor was limited to Surveyor, and by 1970 relatively few JPL people had been involved in the early stages of that project. The person most familiar with its operations was Walker E. "Gene" Giberson, who had been Surveyor's project manager. He was appointed MVM '73 project manager in January 1970.

Giberson assembled a small team of individuals, each selected on the basis of his past project experience and his willingness to work within firm budget allocations. The key members of this team included V.C. Clarke, Jr., mission analysis and engineering manager; J.A. Dunne, project scientist; J.R. Casani, spacecraft system manager; J.N. Wilson, assistant spacecraft system manager and N. Sirri, mission operation system manager, This team, trim in size yet representing broad experience, represented the core of MVM '73 project management.

The Guidelines

At first, the team spent considerable time developing the project's operating concepts and indoctrinating everyone involved with the organizational and project philosophy. They set and held to the following guidelines throughout the project:

- Establish early project guidelines, objectives and constraints
- Use a small staff for planning
- Prepare detailed plans and tasks before initiating a contract:
  - Specific and detailed RFPs
  - A careful tradeoff assessment between JPL and contractor furnished equipment
  - Use of existing documents, reports, and systems
  - Careful selection of fee approach
- Establish cost-at-completion planning, budgeting and emphasis
- Secure all contracts before starting work
- Keep work and budget plans up-to-date
- Exercise organizational impedance matching and communications
- Maximize technical interaction
- Use the concept of cognizant work unit engineer
- Hold frequent face-to-face meetings of operating managers
- Identify and resolve problems promptly
- Make periodic status and performance reviews
- Indoctrinate all involved with cost goals
  - Instill cost consciousness
  - Make cost goals believable
  - Develop a clear understanding of the cost-control system

- Bring manpower onto the project and move it off in a timely manner

The Hot Seat

The Headquarters Program Office/Center Project Office interface can be extremely critical to the success of a project. If the program manager and project manager have differing ambitions and objectives or, as occurred in some instances, an adversarial relationship, the project can suffer. N. William Cunningham, the Headquarters program manager, and Gene Giberson, the JPL project manager, enjoyed an open and forthright relationship, a cornerstone of a sound management structure.

The person on the "hot seat" for cost management is, however, the project manager. The project manager is the one most responsible for establishing the attitude and the framework for the daily tradeoffs of cost, performance, and schedule where it is most essential to maintain a proper perspective. Without his cost consciousness, his basic approach to costs, MVM '73 would not have enjoyed it obvious cost success. This cost attitude is the more unusual since NASA had previously stressed technical performance and schedule requirements over cost as a discipline.

The Science Steering Group selected in September 1969 held its final meeting in March 1970. In its report, the SSG recommended a minimum science payload composed of a plasma science experiment, a magnetometer, an infrared radiometer, an ultraviolet spectrometer, a television system, and an energetic particles experiment.

One of the tasks of SSG was to make a detailed cost estimate for each potential experiment—including design, development and fabrication costs of the hardware, cost of personnel support for launch and mission operations, and cost of data analysis and interpretation and publication of results. These cost estimates, plus a project estimate for integrating the instruments into the spacecraft, shaped the first science budget for the project at $13 million.

An Announcement of Flight Opportunity (AFO) issued in March 1970 invited proposals for experiments. It stressed the intent to select only proven flight-qualified instruments. The AFO also stressed the desire to minimize documentation and stated the intent of JPL to monitor development of the instruments only at the interface level.

Forty-six proposals were received and evaluated. After ranking them in terms of science excellence, technical and engineering requirements, cost and system integration, the program office recommended seven payloads to the OSSA Associate Administrator. The payload cost estimates went as follows (in millions of dollars):

Television	$6.226M
Radio science	0.500
Ultraviolet	0.575
Infrared	0.928
Magnetometer	0.688
Energetic particles	0.383
Plasma science	0.945
Total	$10.245
Instrument integration	2.355
Total	$12.600

To each of the principal investigators selected, Dr. Naugle addressed this comment: "I must emphasize, once again, that the total negotiated figure (dollar cost as selected) cannot be exceeded. Accordingly, I have instructed the JPL Project Office that in the event of an anticipated cost overrun, their alternatives will consist of helping you to reduce the scope of your experiment, or recommending its termination."

Science and Dollars

Whereas most past selections had been considered final at the time of announcement, the letter from Dr. Naugle clearly pointed out that the selection was to be considered tentative until the investigators and JPL completed negotiations. A process of fact-finding and negotiation between JPL and each of the scientific investigators followed, which resulted in well-defined relationships before the major development effort commenced.

It was made clear in the selection and negotia-

tion process that the principal investigator was responsible for the implementation and development of the investigation, including the instrument. The project office followed through on the intent to control principally at the instrument/spacecraft interface level. The systems contractor was responsible for integration of the instruments into the spacecraft.

One innovative technique required the systems contractor to "sign off" on changes to experiment interface drawings, although the contracts for the experiments were between JPL and the investigator. This technique provided greater assurance that the systems contractor was aware of the latest configuration of the experiment hardware, and helped avoid surprises at the time of integration.

Dr. Naugle views MVM '73 as the most successful development of scientific instruments within tight cost constraints. The addition of the experiment integration costs to delivered cost brings the total for science very close to but within the original budget of $13 million.

Meeting payload cost goals begs the question whether controls compromised the science investigations. A detailed review of the development history of each instrument clearly demonstrated that not only was there no compromise of the investigations during development, but that significant capability was added to several investigations. Any science compromise on MVM '73 reflects directly the original constraints established before experiments were selected. The decisions to tightly constrain payload costs, to fly only proven instruments, and to apply go/no-go cost restrictions on instrument development are serious policy decisions to be carefully weighed and considered. They cannot be applied to every payload but they paid off in MVM '73.

NASA and JPL held an industry briefing in February 1970 to apprise companies of the goals and constraints of the MVM '73, to provide detailed technical and program information for early planning, to encourage competition, and to enlist industry's help in determining an optimum role for a system contractor. Forty-one firms attended the briefing.

JPL asked the companies for suggestions regarding implementation of the systems contract approach; separate day-long meetings were held with the most interested competitors to discuss their suggestions. During these meetings, the companies made recommendations on contract scope, roles and relationships, Mariner technology transfer, contract type, GFP handling and other areas they believed were important to the success of the effort.

A procurement plan evolved in which the systems contractor would have the major role (1) to design, fabricate, assemble, and test one flight spacecraft, one test spacecraft, associated test models, test and support equipment and appropriate spares; and (2) to provide level-of-effort support to JPL in mission analysis and engineering, JPL subsystems activities, and mission operations.

RFP Features

The JPL project definition effort had been proceeding for a year at the time the Request for Proposals (RFP) was issued. The result of that effort was a very detailed, explicit RFP. It was an extensive compendium explaining project objectives, project organization and implementation, schedule, project control dates and documents, work breakdown structure, spacecraft design summary, scope of contract, general description of work, JPL/contractor relationships, and mission operations. Its most unusual features included these:

- A spacecraft systems specification which attempted to state only minimum requirements.
- The predetermined intent to divide all work into discreet work units (which allowed separation of responsibilities and facilitated work description, understanding, negotiation, and JPL monitoring). The definition of each work unit was written in a standard format.
- The request for firms to propose overhead cost ceilings.
- The request for baseline and alternate cost proposals to get the best cost mix between JPL and contractor-furnished equipment.

- A call for incentive proposals which gave heavy emphasis to cost, but also statedstrong preference to award fee.
- Emphasis on minimum documentation and maximum use of procedures, forms, techniques, etc., that the contractor currently used.
- Detailed documentation covering Mariner '69 hardware, Mariner '71 hardware, and other JPL-furnished equipment, along with drawings, schematics, processes and procedures to assure full use of the Mariner heritage and facilitate cost estimates.

Four proposals were received. The Source Evaluation Board presentation was made to the NASA Administrator on April 28, 1971, and The Boeing Co. was selected as the systems contractor.

Holding Out for a Firm Negotiated Contract

The pressure to award the contract and commence work was very strong following the April selection, but the project manager and contract manager held out for a firm negotiated contract before allowing work to be started. Within six-and-one-half weeks after selection, the negotiations were completed and a definitive contract was awarded. Work started on June 17, 1971.

The contract, a cost-plus-award-fee type, emphasized the contractor's complete responsibility to meet the spacecraft system performance requirements. The contract effort was divided into work units, each assigned to a manager within The Boeing Co. The work units included in the contract were compatible with both JPL's technical division organization and Boeing's project structure.

Controlling Overhead

A serious concern in systems contracting had been the inability to predict overhead costs. The parties agreed that a ceiling on overhead costs would be negotiated into the contract. Such ceilings on overhead are unusual in normal circumstances, and all the more so in this case, considering the depressed economic situation The Boeing Co. faced in the spring of 1971. The ceiling on overhead never was invoked because Boeing actually underran the negotiated overhead cost.

There were strong cost incentives negotiated into the contract and a process for evaluation and award was developed with emphasis on performance and cost control. The award fee provisions and the system employed to carry them out appear to have been effective in contributing to the contractor's performance. Benefits included these:

- Boeing's spacecraft program manager had the opportunity to increase the fee significantly. The award fee structure allowed broad latitude in the approach to cost and performance tradeoffs.
- The process enforced periodic, results-oriented evaluations and communications at all levels. The process and the resultant dialogue tended to remove the obstacles that stand in the way of the natural motivation to do a good job. By clarifying goals, establishing emphasis, eliminating misunderstandings, and highlighting problem areas for mutual attention, obstacles were removed or reduced.
- Attention of the contractor's top management was obtained by the formal feedback process (briefings supported by letters).

Category of Indirect Expense	CY 1971 Negotiated Per Contract	CY 1971 Actual	CY1972 Negotiated Per Contract	CY1972 Actual
Engineering	$3.94	$3.74	$4.14	$3.88M
Manufacturing	4.99	5.08	5.24	4.97
Productive Material	10.5%	7.9%	10.5%	6.7%
Subcontract Material	6.1%	5.5%	6.1%	3.6%
Area Administration	15.1%	14.35%	15.1%	11.9%
Group Administration (remote)	9.6%	9.75%	9.6%	7.8%

- The discipline of the award fee evaluation process improved JPL's internal communications at all levels, including top management on the award fee review board.

Tight Control

JPL has a reputation in the industry for aggressive contract management, often expressed as complaints of "too tight control" by subcontractors. But the JPL system proves effective in assuring performance.

In MVM '73, change orders were kept to a minimum throughout the contract and were negotiated into the contract promptly after issuance. Project office personnel monitored Boeing's work very closely. The work unit breakdown made it possible for cognizant JPL engineers to thoroughly understand the job, follow its progress in detail, and identify potential problems early.

Early identification of problems coupled with open, candid discussions among The Boeing Co. and JPL managers were basic contributors to the success of the project. D.T. Gant, contracts manager, L.V. Burden, financial manager, and L.M. Bates, cost analyst, who were collocated in the project office, effectively kept the project managers alert to unexpected deviations.

The NASA Management Audit Office, not noted for its approbative descriptions of NASA operations, gave this appraisal: "In our opinion, the JPL surveillance of the contract, its assignment of capable and motivated personnel to monitor the performance of MVM '73 on a full-time basis, and the apparent stringent cost controls implemented by The Boeing Co. before contract award, and retained throughout the program, contributed to Boeing's successful cost performance under MVM '73."

Good Communications

Stressed by the managers, good communications led to early anticipation and resolution of issues and the timely availability of data for decision making. Some of the techniques used to assure good communications included:

- A weekly "Agreement/Disagreement Log," maintained by work unit personnel and reviewed by the JPL spacecraft system manager and The Boeing Co. spacecraft program manager.
- Weekly face-to-face meetings between the systems contractor, systems manager and the systems contractor program manager.
- A weekly summary of agreements and formal tracking of action items.
- Daily meetings between The Boeing Co. test and operations representatives and the JPL resident staff during the system test period.
- Weekly "Problem TWX."
- Formal monthly progress reviews to give an overview and detailed status and plans with particular emphasis on problems.
- Easy access to The Boeing Co. and JPL top management (above the level of project personnel).
- Attendance at award fee briefings by Boeing's top management.
- An extensive and definitive award fee letter and briefing, held not later than 15 days after the end of each period.
- Rapid escalation of significant problems to the appropriate management level for resolution.

None of these actions should surprise good managers, but taken together, they may not be commonplace. These combined techniques greatly helped the MVM '73 project meet its goals.

Highlights of Contractor Performance

The Boeing Co. faced an uncertain general business position at the time the MVM '73 project contract was issued. Major reductions had been made in Boeing's commercial airplane operations, and significant reductions in employment had been made at Boeing Aerospace Co.

Despite the drastic reduction in backlog and direct workload, Boeing was able to reduce overhead costs and even underrun the overhead projections on the MVM '73. The aerospace industry and its government customers are conditioned to the increase of overhead runs when the direct base decreases. This "fact" is considered by many to be axiomatic and inviolate—overhead

costs regarded as "fixed" or unalterable and necessary to support the base for doing business. The example of Boeing's experience in 1970 and 1971 could be a good case study in ways to reduce overhead expense as the direct base decreases.

E. Czarnechi served as The Beoing Co. MVM spacecraft program manager from the early proposal phases in 1970 through early 1973. H. Kennett served as deputy program manager and succeeded Czarnechi. Their participation contributed immensely to the success of MVM '73. They have reviewed their experience, and underscored these management concepts and techniques employed on MVM '73:

- Spacecraft requirements must be defined clearly and early.
- Match people (skills) to work unit tasks.
- Use the "cognizant work unit engineer" concept
- Select the baseline configuration early.
- Implement a system of program reviews and reporting with joint chairmanship by contractor and customer.
- Define and assess technical performance, schedule, and cost risks, and develop work around plans.
- Educate key personnel in the company's cost-accounting system so that when tradeoffs and decisions are to be made, all factors are properly considered and their true impact on cost understood.
- Shorten and improve communications through collocation and program organization
- Establish organizational relationships (e.g., JPL/Boeing) and communication channels early.
- Motivate people through performance assessment, promotion, compensation, and achievement awards.
- Emphasize cost trades during design phase.
- Ensure that only essential work is accomplished.
- Use an objective performance measurement system.
- Rely on each cognizant work unit engineer for early identification, reporting and, when feasible, problem resolution.
- Use dedicated manufacturing and test facilities.
- On-load and off-load manpower in a timely fashion.
- Use recovery ("tiger") teams to work problems. Teams of specialists from outside the program can be assigned problems and provide instant expertise without a continued expense to the program.

A Postscript

The MVM '73 spacecraft (Mariner 10) was launched on November 3, 1973. A number of problems developed early in the flight, but none degraded the mission and none was the obvious result of actions taken to control cost. The spacecraft reached Venus on February 5, 1974, and returned a full set of scientific data, including more than 4,000 pictures. The gravitational attraction of Venus altered the spacecraft's flight path as planned, swinging it toward Mercury. The spacecraft passed within 500 miles of Mercury's surface on March 29, 1974, and returned the first close scientific observations and pictures of the planet.

The project is currently [1974] anticipating a modest underrun at completion. So MVM '73 more than met its original performance objectives and, in addition, served to work out management approaches and techniques to control costs.

Science Cost History

Experiment	Appointment Letter Cost/ OSE[1]	Original Negotiated Cost (March 30, 1971)	Estimated Cost-at-Completion $(October 31, 1973)	±Cost-at-Completion
Infrared Radiometer	$ 789,000/ 21,000	$ 759,000	$ 726,000	- $84,000
Plasma Science	945,000/ 75,000	1,020,000	1,020,000	0
Charged Particle Telescope	383,000/ 8,000	391,000	505,000	+ 114,000
Magnetic Field	685,000/ 25,000	710,000	671,000	- 39,000
Ultraviolet Spectrometer	575,000/ 24,000	575,000[2]	705,000	+ 106,000
Television Science	475,000/---	475,000	555,000	+ 80,000[3]
Radio Science and Celestial Mechanics	500,000/---	500,000	500,000	0
	4,505,000	4,430,000	4,682,000	+ 177,000
TV System	5,751,000	5,765,000	5,787,000	+ 36,000
TOTAL	$ 10,256,000	$ 10,195,000	$ 10,469,000	+$213,000

(1) OSE–Operational Support
(2) Did not Include Bench Checkout Equipment (BCE)
(3) Raw Mosiac Costs–Change In Scope

The Shuttle: A Balancing of Design and Politics

by Dale D. Myers

When Apollo was started, and even deep into the program, NASA had very little integrated planning. No one tried to balance efforts between aeronautics and space, or even manned versus unmanned activities. Jim Webb seemed to want to keep his options open until the last minute, and a long range plan would be a deterrent to that idea. Planning groups were set up, but no lasting results emerged. Even the planning of the science experiments for Apollo, worked almost entirely between Manned Space Flight and the Office of Space Science and Applications, was late getting into the system. When it came to real post-Apollo planning, even though there were pockets of studies and interest, no overall plan emerged until 1969. Detailed specifications from the Congress and their staffs were not a major problem. Congress would want to be kept informed about our planning (no surprises) but in general, their role was supportive.

In 1969, the Space Council, under Vice President Agnew, ran a post-Apollo study, with most of the inputs coming from NASA through Dr. Tom Paine, who, as Deputy Administrator, was a member of the task force. Dr. George Mueller, then Associate Administrator for Manned Space Flight, made some strong inputs to the study. NASA's budget had peaked in 1966, but extrapolations based on the strong support of the public led to a very ambitious outlook. As usual, NASA saw the budget reduction as a temporary thing, failing to understand the growing Vietnam budget, and leaders of the Congress and the administration increasingly fearing a failure in space.

The results of the post-Apollo study were:

- First, we must reduce the cost per pound to orbit by a factor of ten. This would be done with a reusable launch vehicle.
- A reusable Space Tug was needed to reduce the costs from low Earth orbit to geostationary orbit.
- We must have a large, Saturn V-launched space station.
- With the Space Station as a base, we must place a permanent colony on the moon.
- Then, we must explore Mars with people.

The 1969 task force study also had some ambitious projections for the near future of American spaceflight: NASA planned to complete the Apollo program by 1972 with the Apollo 18 mission, and Skylab A was to be completed by 1974.

As Associate Administrator for Manned Space Flight, I had some projections of my own in 1970. Skylab B was also planned for early 1976, the first flight of the Space Shuttle in 1976, a large Space Station by 1980, and the beginning of construction on a lunar base by 1985.

In the meantime, after 1967, the NASA budget started falling at about 14 percent per year. Manned Space Flight's budget was cut in half from 1966 to 1971. Part of that decline was because Congress and the administration were beginning to have misgivings about the continued risk of lunar flights. So were some in NASA. By 1970, it was obvious that the decline would continue, and drastic action had to be taken in planning NASA's future.

First, all studies and technologies associated with Mars were stopped. We canceled Skylab B. Then Apollo 18 was canceled (under pressure from Congress). Finally, the lunar base and the large Space Station were deferred, with the final launch of Saturn V then pegged to Skylab A.

As budget pressures continued, we held discussions with European nations to consider their roles in space exploration. We discussed their providing parts for the Space Shuttle, the whole Space Tug and finally settled on Spacelab as an appropriate item for European interests. Many painful diplomatic discussions were held in that series of negotiations. Space Tug was dropped.

The order of priority for the cutback was based on a conviction that if we could just reduce the cost of transportation to low Earth orbit dramatically, the future would fall back in place.

In 1970, we already had underway a Phase A study of the fully recoverable, two-stage Shuttle. Budget pressures from the administration were continuing, and although no numbers had been developed, it was evident that a program above $10 billion would not fly. Industry saw the problem, too, and began to come up with partially recoverable systems. In 1971, the administration began to talk about $5 billion for the development program, and it was clear that we now had to look very seriously at partially recoverable systems. Consequently, many new configurations were studied, leading to a number of possibilities, fully costed and ready for use in cost trade studies.

At about the same time, and after a long debate with the Office of Management and Budget, NASA agreed to demonstrate the cost effectiveness of a reusable shuttle system. This decision had an enormous impact on the design decisions for the program.

We hired Mathematicians, with Dr. Klaus P. Heiss as the project leader, to run a total cost versus total savings study for a 20-year period. The key cost data for this study was the development costs, the cost per flight, the number of flights per year, and Shuttle effects on the cost of payloads.

The Development Costs

A two-stage, fully recoverable launch vehicle was our starting point. We looked at Max Hunter's single stage to orbit model, but decided that the structure weight left us with no reserves. We recognized that with the Saturn V production line being closed down, the vehicle should have a large diameter payload bay to accommodate a future Space Station. We had an agreement with the administration that NASA would pay for development of the Shuttle, and that the Air Force could use it if they paid launch costs. When we made that offer to the Air Force, they agreed, but wanted a cross range capability to return to base during polar launches from Vandenburg AFB. We agreed, because it was becoming obvious that to meet the cost effectiveness criteria, we would need all the launches we could get. As noted above, European space interests had agreed to build Spacelab, thereby adding reusable payloads.

Cost Per Flight

Launch costs were badly underestimated. Almost all our emphasis was put into pushing down the development costs to get under the administration's bogey. Although President Nixon was a space buff, I am convinced that he and OMB were in lockstep in demanding a less costly Shuttle. Unfortunately, we relied too heavily on airline-supplied data on what this airplane-like device could cost per flight if we followed airline maintenance and on-line checkout rules. NASA's lack of an operations voice at or near the top of the agency caused us to naively believe (or hopefully believe?) that these very low costs per flight could be met. In retrospect, I have become convinced that *some* of the projected launch costs reductions could have been obtained, had the entire design team concentrated on operations as strongly as they concentrated on development.

Number of Flights Per Year

I believe our final cost effectiveness study was based on 50 or 60 flights per year. After all, we were going to have drastic reductions in cost per flight, particularly at high flight rates. With the airline industry's advice that we could check the Shuttle out like a commercial transport, our projections of manpower at the Cape were much smaller than for the Saturn program. We had a large projection of Air Force payloads, the promise of European payloads in addition to Space

Spacelab, and a plan to build relatively cheap scientific payloads that could be modified between flights and flown over and over. Finally, we expected to carry a large number of commercial payloads, most of which would be communications satellites.

The Cost of Payloads

With the Shuttle's capability to carry bulky, heavy payloads, the concept developed that we could build heavy, simple "I-beam" structures for a space bus system, load them with instruments, and fly them over and over, with a different, or upgraded instrument package. We could leave them in space, and then recover them, modify them, and redeliver them to space. With low costs per launch, and many launches, this projected reduction in payload cost contributed to the cost effectiveness of the system.

The Results

Even with these aggressively cost-effective numbers, the study results showed, that to be fully cost effective we had to go with one of the lowest development cost systems. OMB, I'm sure, expected that result, and Congress liked it because of other budget pressures. Whatever the outcome of the study, the administration had decided that NASA could have any kind of Shuttle it wanted, as long as the development costs were equal to or lower than $5.5 billion. In January 1972, when the Shuttle go-ahead was given by President Nixon, Jim Fletcher got a handshake agreement for an additional 20 percent reserve over my 15 percent reserve (mine was included in the $5.5 billion). That 20 percent reserve, had we applied it to reducing operational costs, could have made a big difference. Unfortunately, the reserve was essentially removed by the administration when a leak occurred and the Wall Street Journal reported that the cost could run as high as $6.6 billion.

Design Considerations

While the cost effectiveness study was going on, some important trade studies continued throughout the Phase A, Phase B, and Phase B+ studies carried out by industry. Decisions were made at the top level of NASA on items that affected the Program Authorization Document. These included the studies that led to a blended delta wing rather than a straight wing, the choice of parallel boosters rather than a series booster, solid strap-ons rather than liquid, the payload bay size (length and width), payload weight, and cross range.

A report written by Charles Donlan in 1972 (following this article) summarized the wide ranging configuration studies done between 1970 and the end of 1971. It is important to note that in many cases, decisions were made which reduced the development cost at the expense of operating costs. The choice of solid boosters is a case in point. NASA had extensive experience with liquid boosters, but there was overwhelming evidence that solids would be over a billion dollars less expensive to develop than liquids.

There was also a 100 percent reliability record for large solids at that time. In the final review concerning choice of solids or liquids, we were presented evidence that we could cancel the solid motor thrust in flight, and even abort from them. Later, we found that we could not escape from the solids, but would be better off riding them out. But, at the time, we had concluded that we had very low development cost, very high reliability, an abort capability, and a means of reducing the cost per flight by recovering and reusing the solids.

Postscript

NASA did well in meeting the development cost set out for the program. They missed it by about 5 to 10 percent in 1971 dollars.

They missed badly on operational costs. First, the airline idea of designing with triple redundancy, but flying with a system out, was naively accepted at the time, but was never possible in manned flight. The risk, and the relatively undeveloped systems, could not be compared to commercial aircraft's 30 years of evolutionary development. Second, with NASA's approach to checking all critical circuits and understanding the personality of all components used for our manned flights, there was no way we could come.

come close to the number of 50 to 60 flights per year used in the study (and flights per year is the dominant factor in cost per flight).

A rough estimate of how well we did in operations costs can be reached by correcting our 1971 figures for the increase in cost per flight resulting from flying 12 per year rather than 50, and then comparing those costs to those corrected estimates from 1971 (in real dollars). We still missed our costs per flight by a factor of two or three. Lost over the years, however, was the fact that the original costs per flight were based on accounting only for the "additive costs," over and above the personnel who would be in place if we did not have a Shuttle.

There have been a few ruggedly designed payloads, but there was never a NASA directive to have any. There have been a few payloads recovered, and a few fixed in orbit, but the bookkeeping doesn't show a reduction in transportation cost to give credit to the transportation system.

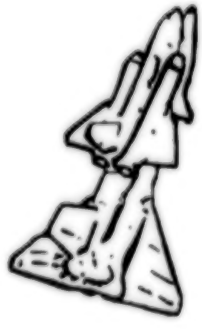
All things considered, I judge the Shuttle to be a resounding success. It has done everything in space that we set out to do. Perhaps, considering the 1970 budget setting, there was no other way to get a program going than through the somewhat ethereal cost effectiveness approach that was taken.

The configuration of the Shuttle has been superb. To fly from Mach 25 to a perfect landing is a major step forward in aeronautics, but to do it with the configuration that was defined at the end of phase B is a tribute to the team of NASA and industry personnel who defined it.

Finally, the Program Authorization Document system worked. That relatively limited set of requirements, approved by the Administrator or the Deputy, brought stability to the program. No change to those few top specifications could be made without convincing the Administrator of the need. That was priceless in holding down changes during the development program.

Shuttle Comparison

Fully Reusable

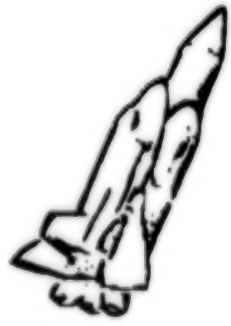


External LH2 Tanks

F-1 Flyback

Series Liquid

Parallel Liquid



Parallel Solid Rocket Motor

Space Shuttle Systems Definition Evolution

by Charles J. Donlan

Acting Director, Space Shuttle Program

July 11, 1972

The initial studies, begun in 1969-70, addressed a fully reusable shuttle system which emphasized minimum refurbishment, autonomous on-board checkout, minimum turnaround time, and the lowest operational cost of any system studied. The operational cost, about $4 million per flight, is about the same as for the Thor Delta launch vehicle—the most widely used launch vehicle in the United States. The development costs of the fully reusable system, however, approach $10 billion and reflect the extensive research and development activity associated with developing two large piloted vehicles that possess both the features of a rocket launch vehicle and a hypersonic aircraft.

Further studies yielded a system with a smaller, more efficient orbiter by the use of expendable hydrogen tanks, rather than propellant tanks located in the orbiter. The booster staging velocity was lowered from 11,000 feet per second for the fully reusable system to 7,000 feet per second. This allowed use of a heat sink booster so that the development costs were lowered to $8 billion. The expendable tankage, of course, meant somewhat higher operational costs of $4 million per flight. The high risk and high peak annual funding associated with developing two piloted vehicles still existed and studies for lower cost systems continued.

Eventually, by removing both the liquid oxygen and liquid hydrogen from within the orbiter, NASA was able to devise a much smaller, lower cost orbiter with a single expendable combined propellant tank. The size of the orbiter and its development costs were dramatically reduced while retaining equal performance capability by utilizing this expendable tank for both liquid propellants. The selected orbiter is a delta wing aircraft, powered by high pressure hydrogen-oxygen engines.

Time phasing some of the orbiter subsystems received considerable study effort. This was known as the Mark I/Mark II shuttle system. The Mark I orbiter was to use available ablative thermal protection, a J-2S engine developed as a extension of the existing Saturn J-2 engine, and other state-of-the-art components such as existing avionics. Improved subsystems such as fully reusable thermal protection and the new high pressure engine would be phased into later orbiters to achieve the operational system (Mark II). This time-phasing reduced expenditures early in the development cycle, but the Mark I system had reduced payload and cross range capability as well as an increased turnaround time of one month. This represented a severe loss in operational capability. Furthermore, the total development costs to achieve the full Mark II system actually increased.

Additional studies indicated that further reductions in orbiter development costs could only be achieved at the expense of compromising the objectives of providing the required flexible orbital capability at low operational costs. The possibility was considered of reducing total systems costs through reducing the size of the payload bay in the orbiter from 4.6 × 18 meters (15 × 60 feet) to 4.3 × 14 meters (14 × 45 feet) and reducing the payload capability for a due east launch from 29,500 kilograms (65,000 pounds) to 20,400 kilograms (45,000 pounds). The additional cost savings were estimated to be only about $70 million in the development program. Furthermore, the orbiter with the smaller payload compartment was unable to accommodate about 10 percent of the projected civil missions and about 37 percent of the projected military missions for a typical mission model for the period 1979 - 1990. Therefore, the smaller shuttle would have required retention of large expendable boosters in the U.S. launch vehicle inventory to handle the larger payloads, thus incurring higher costs than were achievable with the baseline shuttle system.

The Mark I/Mark II concept would have used Saturn F-1 engines but nevertheless would have been a costly and relatively high-risk undertaking since, again, two manned returnable vehicles were required to be developed. Its development cost was estimated at between $6 and $7 billion with a cost per flight of approximately $7 million. In a further attempt to reduce the development cost, studies were initiated to examine a shuttle configuration utilizing an unmanned ballistic booster.

Evolution to the Current Shuttle Configuration

The introduction of the external tank orbiter had a major impact on the booster element of the shuttle system. Since the orbiter became much more efficient, it became possible to let it take even more of the burden of propelling the shuttle into orbit. Staging could therefore occur at about 5,000 feet per second. An important advantage from the use of the external tank orbiter was the opportunity to utilize ballistic liquid boosters or solid rocket motor boosters that are efficient at the lower staging velocities. Their use promised the greatest reduction in development costs.

The ballistic unmanned booster studied included both pressure-fed and pump-fed liquid propellant boosters and solid propellant boosters. The two liquids compared as follows:

In the pressure-fed system, the engine would have been a major new development. In the pump-fed system, it would have been a modified F-1 engine (the engines used in the Saturn V booster).

New manufacturing techniques would be required for the pressure-fed booster; conventional techniques developed for Saturn would be used for the pump-fed.

Major modification of facilities would be required for the pressure-fed booster; to a large extent, existing facilities could be used for the pump-fed booster with minor modifications.

The stiff, thick walls of the pressure-fed booster could withstand a moderately high impact velocity, and thus it lent itself to booster recovery. Recovery of the thin-walled pump-fed booster appeared to be of much higher risk.

It was concluded that the pump-fed system had cost advantages and lower technical risk in all aspects except the recovery risk, which appeared large. Of the two liquids, the pump-fed concept was deemed more advantageous in spite of the need to develop complex recovery systems.

After we examined the liquid booster class, a comparison was then made against solid rocket motor configuration. Conventional expendable pump-fed systems currently exist in the series burn configuration where the orbiter engines are ignited after booster shutdown and separation. However, a parallel burn configuration where both booster and orbiter engines are ignited at liftoff takes maximum advantage of the high performance orbiter engines. This parallel burn configuration is particularly attractive for the solids where it is desirable to stage at a low velocity and to minimize the size of solids for operational cost reasons. The pump-fed liquid booster in the series configuration was therefore compared with the parallel burn solid rocket motor booster.

Due to the high cost for each pump-fed booster, recovery refurbishment and reusability are essential, while for the SRM this is not so critical. Essentially, the net cost of losing a liquid booster would be much greater than losing a solid, jeopardizing the ability of the shuttle to attain the low costs of recurrent operations. In addition, providing recovery would entail major developmental risks for the liquid but would be simpler for the solids.

Development costs of the solid booster are estimated to be about $700 million fewer than those of the liquid booster. Environmental effects for both liquid and solid systems were about the same with one exception—propellants and their exhaust products. The liquid booster would use RP, a kerosene-like rocket propellant, and liquid oxygen, and its exhaust products would be chiefly carbon monoxide, water vapor, and carbon dioxide, along with smaller quantities of hydrocarbons and ammonia. The chief emissions from the solid rocket motors are hydrogen chloride, carbon monoxide, water vapor, and aluminum oxide.

It was finally determined that, of the unmanned ballistic boosters, the solid booster recoverable system with parallel orbiter burn would give the lowest development cost ($5.15 billion), least capital risk per flight, and lowest technical risk of development. In addition, economic studies have shown that this system will provide the highest rate of return on investment. Environmental effects would be minor, although it would be necessary to impose additional but acceptable constraints on launches associated with the likelihood of rain.

Summary

Preliminary design studies of the initial two-stage fully reusable concept showed that the size of the system and its development cost could be greatly reduced through the use of an external expendable liquid-hydrogen tank for the orbiter, with a small increase in operating costs per launch. Further study showed that additional cost savings and technical advantages in the development program would accrue if both the liquid-oxygen and liquid-hydrogen for the orbiter were carried in an external tank jettisoned from orbit. This change permitted the orbiter vehicle to be significantly smaller and more efficient, thereby simplifying the booster development and reducing substantially the development and procurement costs at the expense of some additional increase in the recurring cost per flight. Consideration of all factors led to the selection of the solid rocket motor booster, parallel burn system for the Space Shuttle. All configuration comparative issues have been studied in great detail both in and outside of NASA, to evolve this most cost-effective space transportation system.

Resources for NASA Managers

by William M. Lawbaugh

What's New in the Library Collection

Following is a list of books and articles that have most recently been added to the PPM Library Collection. All of the materials may be borrowed through interlibrary loan from you Center Library *except* the Summer Study documentation. (The sheer volume of paper makes this study difficult to circulate.) Call 202/453-8740 or FTS 8-453-8740 for further information.

Project Management Summer 1991 Study documentation, which includes 10 volumes of information plus individual papers and earlier NASA management studies.

The Organizational Behavior Reader
Edited by David A Kolb, Irwin M. Rubin, and Joyce S. Oslond
5th ed. 1991. Call Number HF5548.8 .K552 1991.

Thinking About Management
by Theodore Levitt, 1991.
Call Number: HD31 .L3848 1991.

Quality Training: What Top Companies Have Learned
by Kathryn L. Try
The Conference Board Report Number 959, 1991. Call Number: HF5549.5 .T76 1991.

NASA, Maintaining the Program Balance, National Academy of Public Administration, 1991. Call Number: TL521.312 .N374

A Report by the Academy Panel examining the distribution of NASA science and engineering work between NASA and contractors and the effect on NASA's in-house technical capability.

Business Ethics: Ethical Decision Making and Cases
by O.C. Ferrell, 1991.
Call Number: HF5387 .F47 1991.

CASE: Computer-Aided Software Engineering
by T.G. Lewis, 1991.
Call Number: QA76.758 .L49 1991.

Project Management: How to Plan and Manage Successful Projects
by Joan Knutson, American Management Association, 1991.
Call Number: T56.8 .K58 1991.

System Engineering Management
by Benjamin S. Blanchard, 1991.
A Wiley-Interscience Publication series entitled New Dimensions in Engineering. Call Number: TA168 .B53 1991.

A Review of the Office of Aeronautics and Space Technology's Management Processes and Practices
by the National Academy of Public Administration, 1991.
Call Number: TL521. 312 .R48 1988.

NASA Project Status Reports: Congressional Requirements Can be Met, but Reliability Must be Insured
General Accounting Office, GAO/NSIAD-90-40, 1990. Call Number: T58. 4 .U55 1990.

Articles

Risk Management Integration with System Engineering and Program Management,
by G. Vlay, presented at AIAA Space Programs and Technologies Conference September 25-28, 1990. Call Number 91A10139.

The Causes of Project Failure
by Jeffrey K. Pinto and Samuel J. Mantel, Jr. in IEEE Transactions on Engineering Management, Vol. 37, No. 4, November 1990, pp. 269-276.
Call Number: 91A19889.

Can Space Exploration Survive the End of the Cold War?
by Bruce Murray, Space Policy Vol. 7, No. 1, February 1991, pp. 23-34.
Call Number 91A27566.

Risk Assessment and Program Management
Jerold Haber, in Aerospace Testing Seminar March 13-15, 1990, Proceedings of the Institute of Environmental Sciences, pp. 31-38.
Call Number: 91A29698.

Concurrent Engineering: The Challenge for the 90s
by Kevin M. Smith and Carol A. Marlin, presented at National Aerospace and Electronics Conference, May 21-25, 1990, pp. 1313-1323.
Call Number: 91A31023.

The Explorer Platform Planning System: An Application of a Resource Reasoning Planning Shell
by David R. McLean, Brenda J. Page and William J. Potter, in Proceedings of the ESA Symposium June 26-29, 1990, ESA SP-308, October 1990. Call Number 91N22222.

Mars: A Generic Mission Planning Tool
by A. Killner, N. Schielow, F. Zapp, in Proceedings of the ESA Symposium June 26-29, 1990, ESA SP-308, October 1990.
Call Number 91N22238.

Manager's Handbook for Software Development Revision 1
November 1990, Goddard Space Flight Center, Software Engineering Laboratory Series, SEL-84-101.
Call Number 91N15773.

Book Reviews

Government-Industry Project Management Terminology and Documentation Manual
(HD 69 .P75 G68 1991)

This 130-page manual is compiled by an Air Force support contractor in order to serve as a course training tool and to propose standard terminology for the project office, contractor, subcontractor and user. Presumably, when they all speak the same language and mean the same things, teamwork will result.

The loose-leaf *Terminology and Documentation Manual* begins with a rather odd "List of Acronyms and Abbreviations" with only one abbreviation: "Synth." for Synthesizer. Some you will find nowhere else (such as "WAG" for "wild anatomical guess"), while more standard acronyms, such as WAD for Work Authorization Document, or WAN for Wide Area Network, are missing.

Section 2 is a 60-page "Definition of Terms," again somewhat arbitrary and incomplete. Definitions range from the obvious ("Teamwork. Working together to achieve a common goal.") to the oblique ("Tiger Team. Focused visibility, evaluation and recommendations by objective specialists relative to an identified area of concern."). In its "System Hierarchical Structure," a "part" is ranked as lowest and "system" as highest, above "element" and "segment."

Section 3 is "Control State Descriptions," beginning with Source Selection Initiation Review (SSIR) and ending with Operational Readiness Review (ORR). This is perhaps the most valuable part of the manual because of its Q/A format and detail. Section 4, "System Documentation: Content and Outlines," however, is least helpful because of its sketchiness. Section 5, "Symbols," is a mere couple of pages on arbitrary symbols and a master schedule.

This manual, despite its shortcomings, is a start towards a reliable, consistent and comprehensive glossary for project management. A better

one may be the *PPMI Lexicon* by Dennis E. Fielder, available through the PPM Library collection.

Defense Acquisition Management Policies and Procedures
(DoD Instruction 5000.2: February 23, 1991)

In the past, Department of Defense acquisition management policies and procedures were published in dozens of separate directives and instructions. While they were all cross-referenced, they "defied practical use" by managers and contractors alike. This instruction consolidates 45 such documents into about 500 pages for the program manager, milestone decision authorities and their staffs along functional and organizational lines.

Besides general acquisition policies and procedures, DoD Instruction 5000.2 covers requirements planning, risk management, systems engineering, configuration and data management, contracts, program control and test and evaluation activities in support of the acquisition process.

Acquisition in the DoD has been an issue of keen interest in the past decade. Understandably, part of the problem has been the maze of laws, directives and instructions that go in and out of effect. The instruction would go a long way towards fair, consistent and coordinated acquisition in defense programs were it not for its dense, abstract writing.

Systems Engineering Handbook. 2 Volumes
(Systems Analysis Division: Marshall Space Flight Center, 1991)

Faced with the impending retirement of many experienced engineers, MSFC saw the need "to capture their knowledge and make it available to the next generation of systems engineers." The result is two well written, well organized volumes, nicknamed "roadmap" and "toolbox."

Volume I, completed in February 1991, is 117 pages entitled "Overview and Processes," showing "how MSFC does it." After a brief overview of the NASA phased project planning process (phases A to D), Volume I covers the entire systems engineering process from planning and definition to post-mission evaluation. Tying it all together in an elaborate process flow chart, the "roadmap," which is reduced and highlighted in each section to show how the topic fits in the larger scheme of systems engineering.

The "toolbox" of Volume II was completed in May 1990 and is twice as thick. This volume consists of documentation, applicable specifications and standards, analyses and checklist, processes and checklist, and summary of systems engineering tools and models, and a fascinating list of lessons learned from past programs. Each area is replete with templates and fact sheets which explain the tools, techniques, analyses and documentation formats. This volume is not as tightly organized as Volume I, but contains useful, valuable information.

While the text is readable and the figures are clear, some of the schematics in Volume II are overly complicated and the Volume I introduction refers wrongly to the "roadmap" as Figure 12 (not 11). Nevertheless, MSFC's *Systems Engineering Handbook* is a good start in an increasingly important and detailed discipline.

The Space Station Decision: Incremental Politics and Technical Choice
by Howard E. McCurdy
(Baltimore: Johns Hopkins University Press, 1990)

Under contract with NASA, American University public affairs professor Howard E. McCurdy has produced the second in the *New Series in NASA History*. (Henry Cooper's *Before Lift-off* about Shuttle astronauts was first in the series.) It comes right on the heels of Levine and Narayanan's *Keeping the Dream Alive,* which covers much the same time period. Both accounts rely heavily on the NASA History Office and its then director, Dr. Sylvia Fries (spelled "Fires" in McCurdy's acknowledgements) as well as interviews with some of the Space Station Task Force members.

McCurdy's study, by far the most extensive to date, focuses on that "one brief shining moment"

in NASA between Apollo and the present which has captured the imagination of aerospace writers and researchers. The 1984 decision to build the space station says so much about NASA's past and future, but so far none of the original task force members has attempted to tell "the inside story." That story, not fully told in official documents, has been patched together with interviews, usually pointing to a particular theory or thesis.

Professor McCurdy's thesis is implied in the subtitle: "Incremental Politics and Technological Choice," with the further implication that the former affects or even shapes the latter. The thesis is simple: The Apollo decade had focus, purpose and commitment; during the next two decades, the civil space program "settled into the swamp of incremental politics." There was no vision, no goal.

Technological choice is another matter. NASA came up with a way to get Americans to the moon just 14 months after President Kennedy approved the program. President Nixon got a Shuttle configuration in March 1972, within three months of approval. But for space station, "NASA slogged through a series of designs." Remember the power tower, dual keel, single boom, revised baseline and rephasing?

What happened this go-around? McCurdy points to two inherent problems which suggest deception. First was cost. The original $8 billion cost estimate was not at all realistic. Not even a stripped-down station could be launched for that. Secondly, the original space station promised too much to too many. Defense may have wanted an observation post but the Europeans did not want military presence; life scientists people wanted a large, active crew, but materials scientists needed microgravity and Mars-mission people preferred a service station for refueling. The reader is left wondering whether the present-day problems with funding and configuration are a result of raw, deceptive politics or bad technological choices made in the past. Perhaps either or both would be gross oversimplification, as a strong case could be made for other debilitating factors such as history (especially the impact of the Challenger disaster), management (personnel and methodology), age distribution (the natural aging of Apollo-era employees), not to mention public relations or the 1981 tax cut.

Elsewhere, for example, McCurdy has argued that Apollo-era NASA was "hands-on" technologically competent, but later became noted for its contracting out. (See *Space Policy*, November 1989, for example.) Such a theory would either enhance or disprove his thesis in *The Space Station Decision*, but it would more than likely alter the book's subtitle. Perhaps the problem is what appears to be long gap between research and writing. The book came out in late 1990, but most of the firsthand interviews took place in 1985 and 1986.

Nevertheless, the decision to build Space Station Freedom is fraught with intense interest, scrutiny and even mystery. Additional studies of this 1984 decision are forthcoming, and each one will understandably add another perspective, other insights. For now, though, McCurdy's book is *the* book on the subject; for how long depends on insiders or Task Force members who take up the pen.

Project Management Tools for Engineering and Management Professionals
by Adediji B. Badiru
(Norcross, GA: Industrial Engineering and Management Press, Institute of Industrial Engineers, 1991)

This assistant professor of industrial engineering at University of Oklahoma describes his book as "a collection of project management tools . . . for the engineering and management professional." It presumes prior knowledge and previous study of most of these "tools" for none is described or explained in any detail. MBO, for example, is given two thin paragraphs; so is Maslow's Hierarchy of Needs; McGregor's Theory X and Theory Y gets three paragraphs; TQM four. However, an awful lot of "tools" are mentioned in the 428 pages of text and appendices, and in about 150 figures and tables. The tools receiving the most attention are WBS, CPM, PERT, Gantt charts and MARR (minimum attractive rate of return) methods.

If Badiru has a theme or point of view in his compilation, it would be this: "In the real world, there are no right answers. There are only options." He explains that new engineers quickly find that the theoretical and quantitative techniques of project management learned in school do not necessarily apply in the "real" world. More often than not, the practical mana-ger must settle for a "near-optimal" alternative in lieu of a perfect solution. H.A. Simm discovered this reality nearly 40 years ago and dubbed it "satisficing." Badiru applies the concept to project management decision making.

The author is strong on the economic aspects and quantitative analysis of project management, but his most original approach is the area of software tools for project managers. He evaluates 19 software programs, from Microsoft Project to Control Project, most of which can run on personal computers. However, this rather unique effort may also date the book quickly as new software for project management comes on the market and old programs are updated and improved. Even in the time it took to finish the book, prices changed dramatically. Artemis Project, for example, is listed at $5,000 for a single copy in the text but at $3,500 in the Appendix. Likewise, Harvard Project Manager software is listed at $695 in the text but a hundred dollars less 50 pages later. To compensate, another handy appendix supplies addresses and telephone number for major software developers in the field of project management.

Beyond the Myths and Magic of Mentoring: How to Facilitate an Effective Mentoring Program
by Margo Murry, with Marna A. Owen
(San Francisco: Jessey-Bass Publishers, 1991)

A lot of people are talking about "mentoring" these days, yet little is written about it, even though it is an ancient concept. It dates back at least to Homer, who chronicles the appointment of Mentor who looks after Telemachus for a decade until the boy's father, Odysseus, returns from the siege of Troy. Today it is perhaps the latest buzzword in management circles.

Yet, as the authors of this book note, mentoring "has been applauded as the best and criticized as the worst thing that can happen in one's career." They state flatly, "some organizations and some people will never be ready for mentoring."

The authors are president and senior associate of a firm called "MMHA-The Managers' Mentors, Inc.," although the acronym is not spelled out. In trying to explain mentoring, they say it has nothing to do with role models, "distant stars" or sponsors. Rather, they call it "facilitated mentoring" which involves a mentor and a protege in a formal but willing relationship of sharing skills or experience, systematically.

Perhaps the clearest example of a successful mentoring program cited is at Trinity College in Washington, D.C. Here, undergraduate students are paired with alumnae in the same professional field who together negotiate a set of activities they will share over the semester. Companies and government agencies are also cited as having formal or informal mentoring program. The IRS mentoring program in Kansas City, for example, encourages professional and personal growth.

To make mentoring work, the authors suggest a pilot program first, then plenty of planning, training, coordination and evaluation. They are not blind to gender and culture issues in the workplace, such as sexism and racism. Unions are seen as more of a help than a hindrance in the mentoring process, providing grievance procedures and due process when problems arise. They also recognize the Yankee streaks of independence in American business: "We do not have the patience of the Japanese nor the true team spirit of the Scandinavians . . . Meanwhile, divorce statistics in the United States prove that we are becoming worse at managing relationships." The key, the authors say, is "persistence" to bring about the benefits of facilitated mentoring.

So far, "facilitated mentoring" seems to work best in schools and charitable organizations where supports systems are already in place to compensate for the greed, sabotage and selfishness often attributed to people climbing the lad-

der in corporate America. Whether mentoring takes hold in government or industry may depend upon whether the concept is presented in trendy workshops or in serious studies. This book is a modest start.

Engines and Innovation: Lewis Laboratory and American Propulsion Technology
by Virginia P. Dawson
(Washington: NASA SP-4306, 1991)

In 1982 it looked like the beginning of the end for Lewis Research Center (LeRC). Staffing was down from 4,200 in 1971 to just 2,690 in ten years. The 1983 aeronautics budget had been halved by the Reagan budget trimmers. The then-influential Heritage Foundation marked Lewis for extinction in their blueprint, *Agenda for Progress*, by recommending the abolition of all of NASA's civil aeronautics programs. The city of Cleveland had recently declared bankruptcy. And the newly appointed Center Director resigned.

Within five years, Lewis phased out its famed energy research and was no longer a basic research laboratory where most of the work was done in-house. But it was still alive. In fact, employment picked up considerably at Lewis with several new programs, including the Shuttle-Centaur program and the space power system work package for the Space Station Freedom Program. In the words of division chief William "Red" Robbins, "It was a damn miracle!"

Although *Engines and Innovation* is part of the NASA History Series, author-historian Virginia Dawson modestly disclaims this is neither "an administrative history of LeRC nor a chronicle of its achievements." Rather, she says, "I hope that my book is a contribution to the current effort among historians of technology to understand technological innovation as a social activity or process." In that, she succeeds admirably in a well-written book which captures the essence of technology transfer in the NACA and NASA eras. For example, she notes that Case Institute of Technology was on the receiving end of LeRC's expertise in gas turbine and rocket technology until it developed graduate programs and the situation reversed.

Dawson thematically traces the rise and fall and rise again of Lewis Research Center from its creation in 1941 as the NACA Aircraft Engine Research Laboratory (AERL) by NACA Director (from 1924-1947) George Lewis. By the end of the war it became known as the Flight Propulsion Research Laboratory to reflect jet propulsion and rocket research. NASA was formed in 1958 and the lab took on its present name as it began crucial research in nuclear rocket systems at the old Plum Brook Station 50 miles west.

Dawson, a Ph.D. in the history of science and technology from Case Western Reserve, began work on this project in 1984 under contract to the NASA History Office, virtually from scratch. Only one book had been published on the topic, and that covered only liquid hydrogen propulsion at LeRC from 1945 to 1959. An unpublished M.A. thesis helped with the war years, along with personal interviews with such LeRC legends as Abe Silverstein, Ben and Irving Pinkel, and Bruce Lundin. However, the fascinating story, published in 1991, virtually ends in 1984; neither Andrew Stofan nor John Klineberg was even interviewed. She concludes that the challenge for LeRC is to restore "a balance between research and development."

To Engineer is Human: The Role of Failure in Successful Design
by Henry Petroski
(New York: St. Martin's Press, 1985)

"To understand what engineering is and what engineers do is to understand how failures can happen and how they can contribute more than success to advance technology." Thus, Henry Petroski, an engineering professor at Duke University, begins his now-classic study of the human side of engineering.

You do not need to be an engineer to understand, appreciate and enjoy this slim, illustrated book of 250 pages. He begins with a clear account of the 1981 collapse of the Kansas City Hyatt Regency Hotel skywalks and ends with his telling search of a famous Santayana quotation: "Those who cannot remember the past are condemned to repeat it."

Much of the early part of the book is taken up with fairy tales (Goldilocks, the Three Little Pigs) and poetry (Oliver Wendell Holmes' "The Deacon's Masterpiece," about "the wonderful one-hoss shay, that was built in such a logical way") to illustrate his point that "success is foreseeing failure." No engineer wants to learn by mistakes, says Petroski, but there is not enough to learn from successes to go beyond the state-of-the-art.

The hero-engineers are the Roebling brothers (Brooklyn Bridge) and Joseph Paxton, who built the Crystal Palace in Hyde Park. They were engineers who had vision and creativity. His bridge stories are most memorable, especially the undulating Tacoma Narrows Bridge.

In the final chapters, however, Petroski reveals himself as a stick-in-the-mud, an incurable romantic. His narrative "from slide rule to computer" suggests that the latter can be attributed to "computer-aided disasters" such as the roof collapse of the Hartford Civic Center, while the former forces an engineer to rely upon common sense and conventional wisdom in design. Nevertheless, as Petroski admits, it would be impossible to design or build a megaproject, like a nuclear power plant, without computer technology.

One event that makes *To Engineer Is Human* a classic is the fact that a 50-minute film was subsequently made by Films Incorporated, bearing same title, starring the author. In the film version, Petroski begins with the Challenger disaster and ends with a successful night time launch of the Shuttle. Again, the focus is upon bridges, but his humanistic ideas are illustrated nicely with shots of pyramids and cathedrals. The PBS-quality film and book are complementary in showing failure and fatigue as useful design concepts.

Computer Applications for Project Management: An Overview
by Robert Mead, (Huntsville, AL: Carnber Corporation, February 1991)

This brief, 50-page outline of computer applications is a resource for a project manager who seeks information on some very basic computer applications. It is not for the expert. No one needs to be convinced that "computer systems can help the project manager/planner by doing some project management functions better, faster, more accurately." Choosing the systems is the main thrust of this presentation, but, as the author observes, "This is an area of dynamic change." Better to seek out advice from periodicals, professionals, user groups and consultants.

END

FILMED

11/24/92